A Method to Prioritize Sources for Reducing High $PM_{2.5}$ Exposures in Environmental Justice Communities in California

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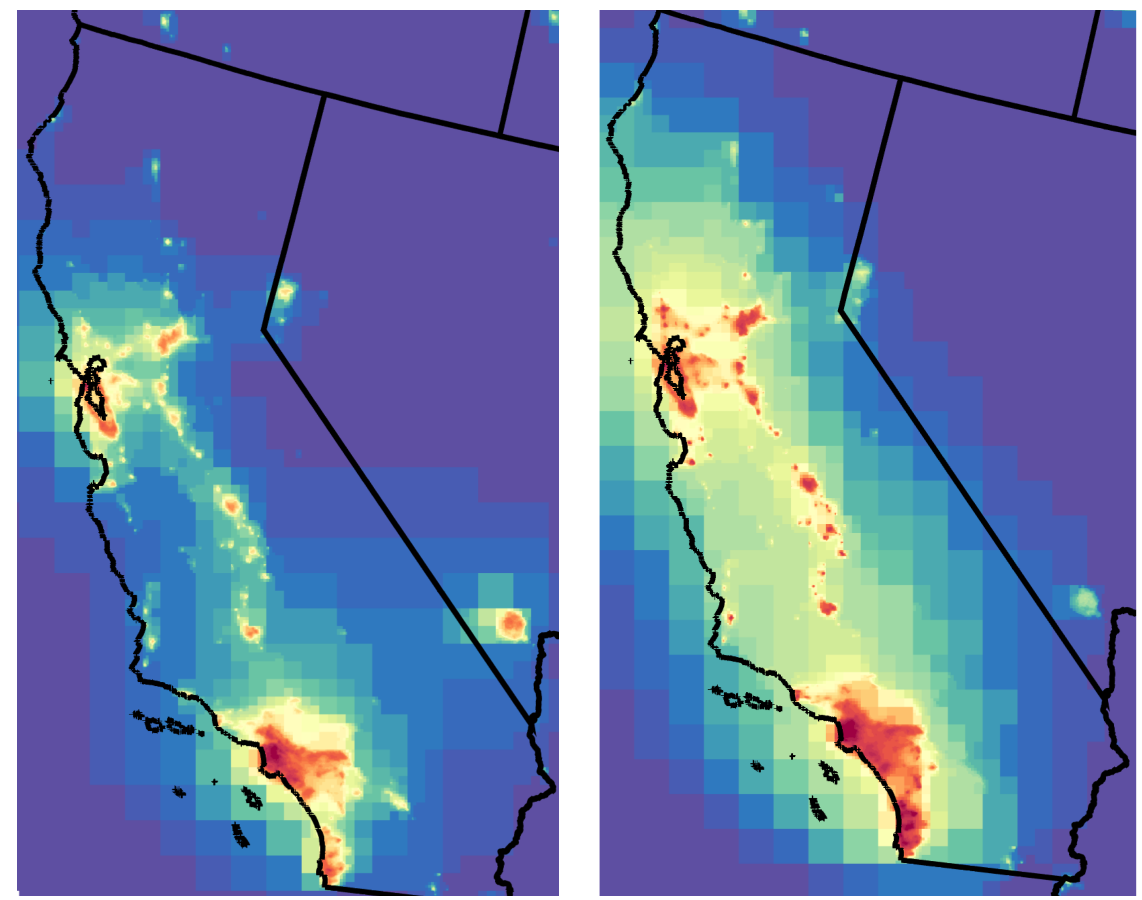

California ARB Research Seminar
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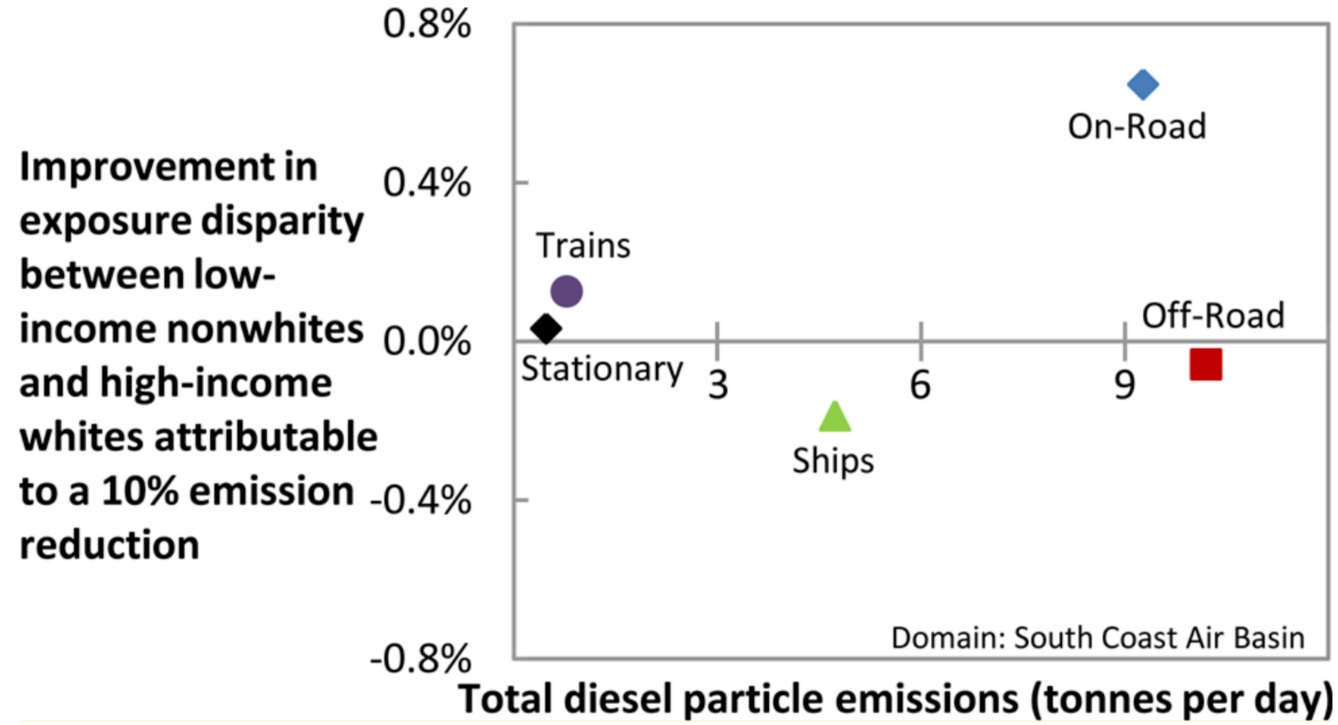
Key findings

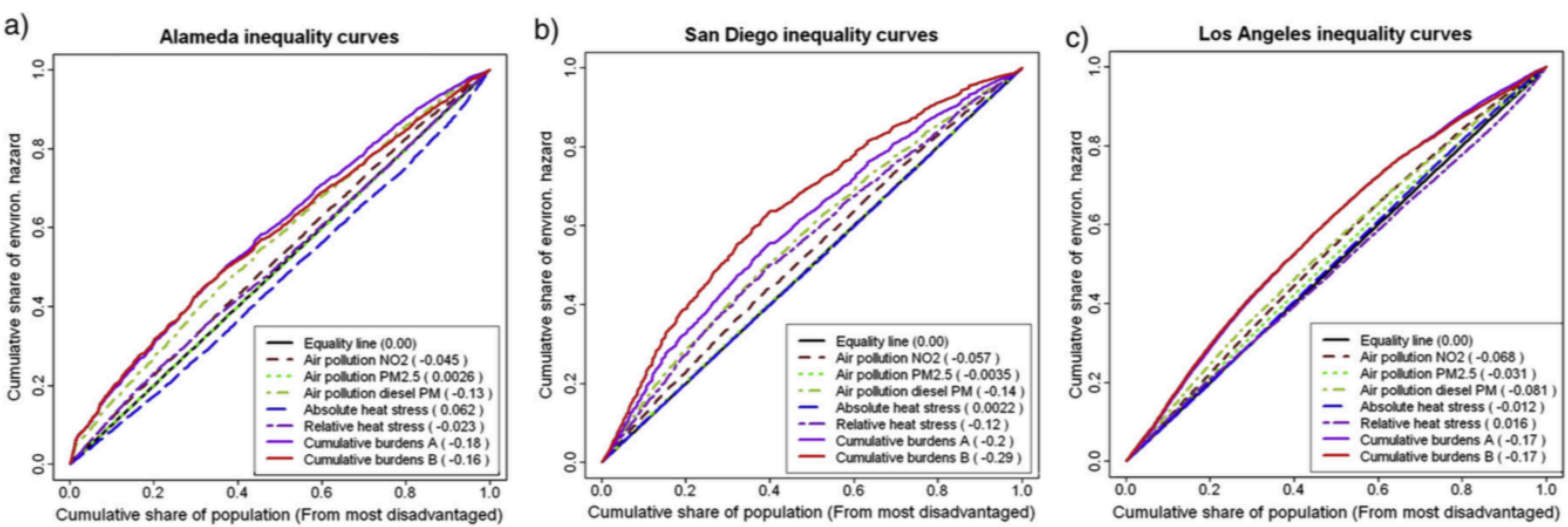
- There is a wide range in the exposure rates, or **intake fraction**, of different source categories and locations.
- We find significant exposure disparity by income, race, and in **disadvantaged communities (DACs).**
- Nearly **all major source categories** in CA contribute to $PM_{2.5}$ disparities.
- Top sources for intake and disparity include the industrial sector, on-road and off-road mobile sources, and the natural gas and petroleum industry.
- The intake fraction database can be used to evaluate the **efficiency of control measures.**

Prior work: EJ and air pollution

Persistent disparities in $PM_{2.5}$ concentrations in California

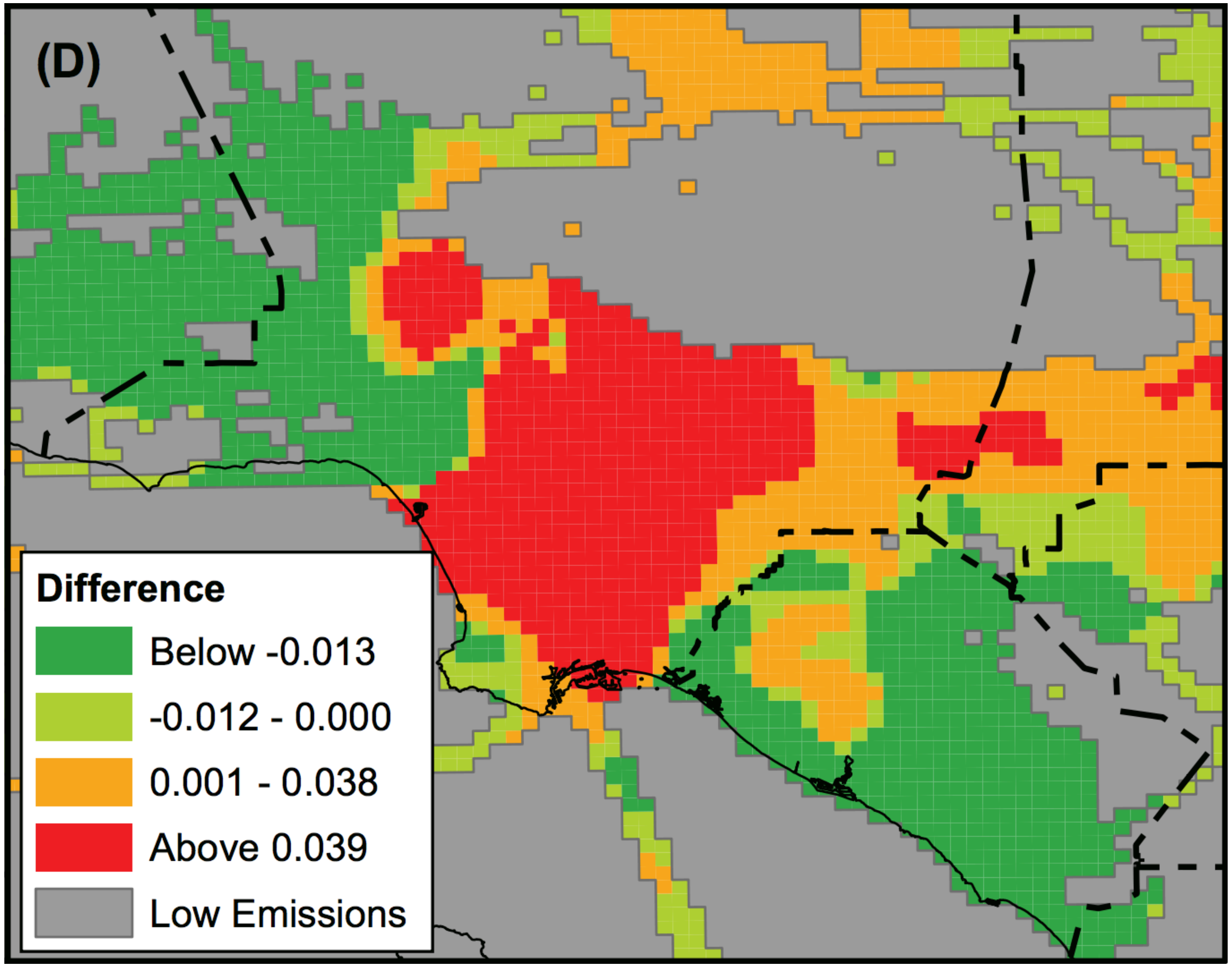


Marshall et al. (2014) *Environ Sci & Tech*



Su et al. (2012) Environ International

Decision-support tools for iF and EJ



- Map shows where emissions of $PM_{2.5}$ from diesel engines cause a greater exposure gap between white and minority populations.
- Colors indicate changes in EJ based on the difference in average air pollution exposure in minority communities vs. white communities.

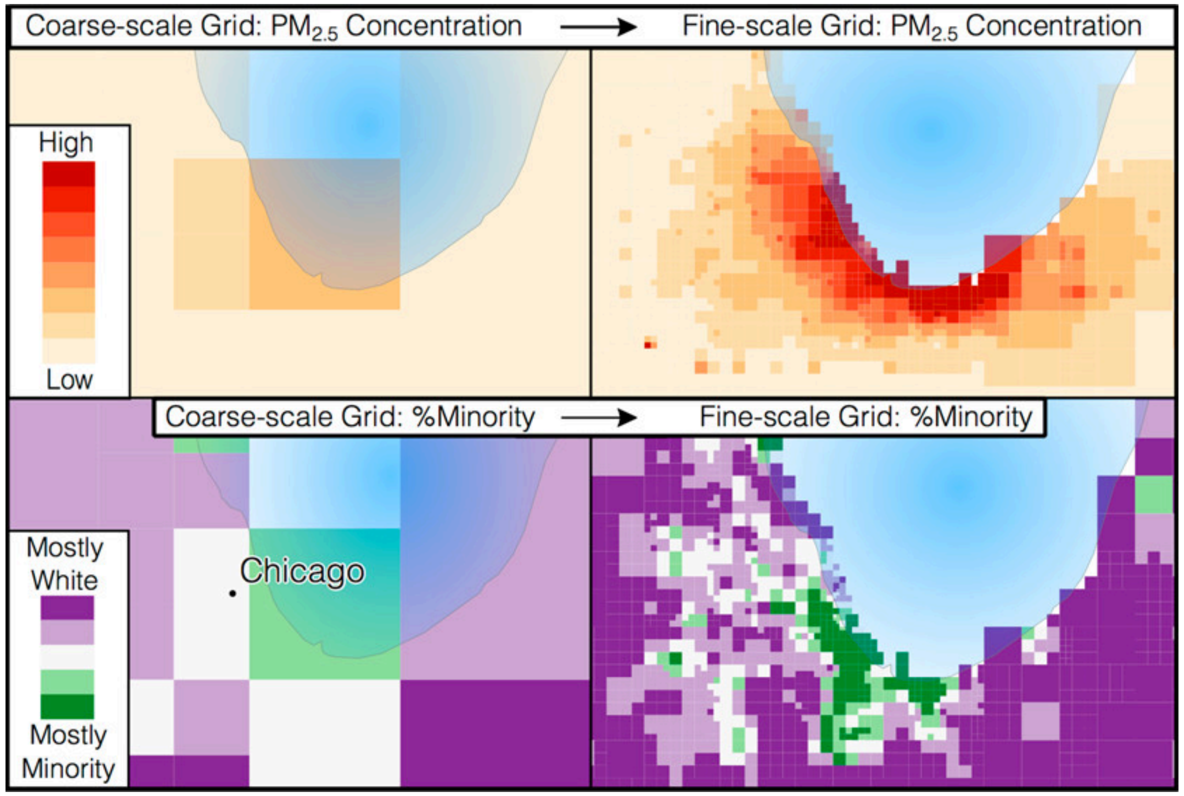
Target emissions in areas where impact and disparity are highest

Nguyen and Marshall (2018) *Environ Res Letters*

EJ research: two key needs

Model at appropriate spatial resolution

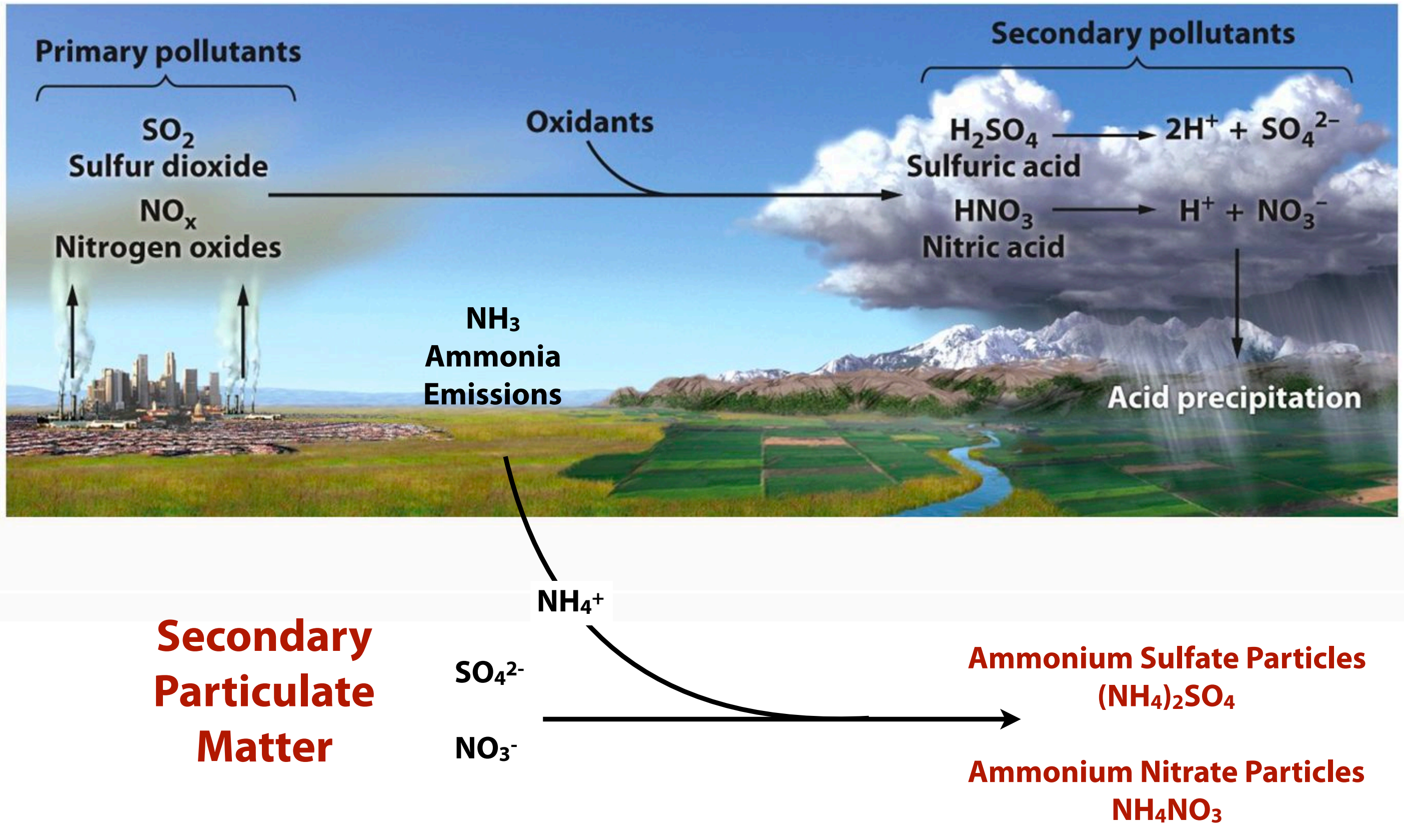
Proximity of emissions and people drives inequalities



Paolella et al., 2018

Include secondary $PM_{2.5}$

Secondary PM generally > 50% of all exposure.



References:

Marshall, J. D., Swor, K. R. & Nguyen, N. P. Prioritizing environmental justice and equality: diesel emissions in Southern California. *Environmental Science & Technology* **48**, 4063–4068 (2014).

Paolella, D. A. *et al.* Effect of model spatial resolution on estimates of fine particulate matter exposure and exposure disparities in the United States. *Environ. Sci. Technol. Lett.* **5**, 436–441 (2018).

Su, J. G. *et al.* An index for assessing demographic inequalities in cumulative environmental hazards with application to Los Angeles, California. *Environmental Science & Technology* **43**, 7626–7634 (2009).

Project objectives

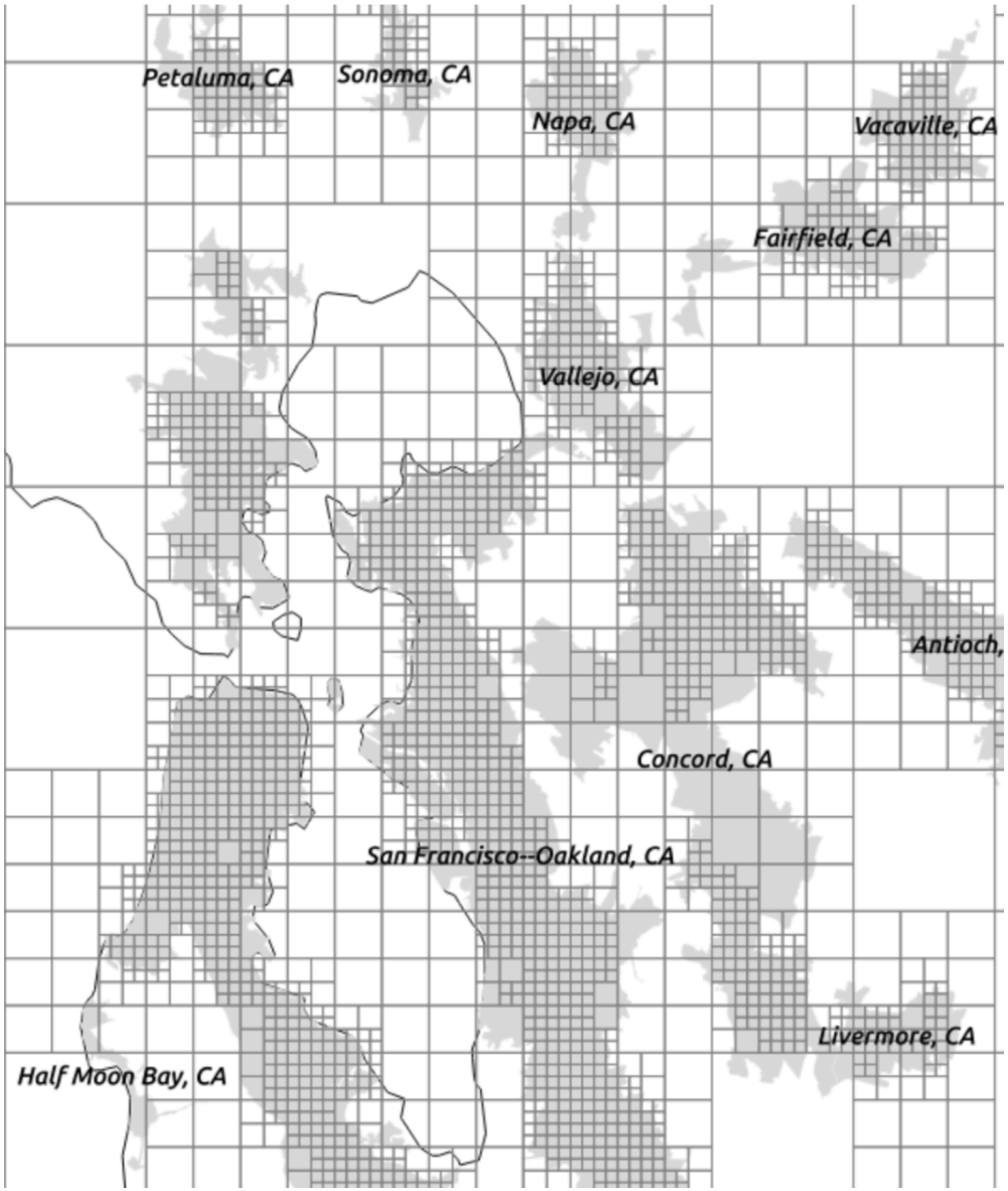
- **Generate comprehensive database of iF and EJ metrics**
  - Location-specific and sector-specific
  - Primary $PM_{2.5}$ and secondary $PM_{2.5}$ (SOA, pSO_4, pNO_3, and pNH_4)
  - Intake metrics by race/ethnicity, income quintile, age, and other socioeconomic groups, including SB 535 Disadvantaged Communities

- **Apply database as screening tool**
  - Model exposure concentrations from 11 major sectors and 59 subsectors
  - Identify top sources contributing to exposure disparity

- **Provide spatial database and summary metrics as tool for comparing policies for exposure reduction**
  - In-person training to follow this seminar

Methods

InMAP: Intervention Model for Air Pollution



Subset of InMAP domain for Bay Area

Reduced complexity model enables 1000s of simulations

Variable grid resolution

- scales with population density
- 1×1 km in urban areas
- 2-12 km in in less dense areas

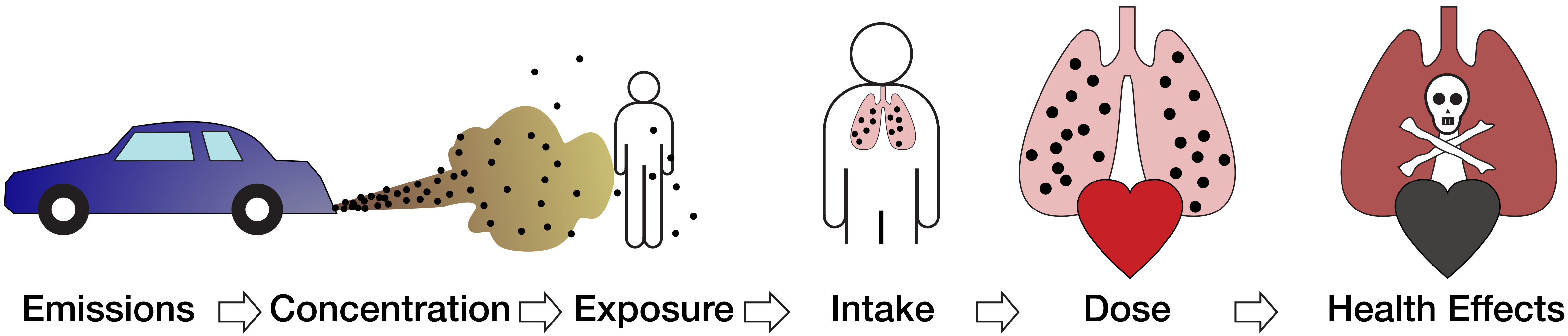
Treatment of secondary $PM_{2.5}$

- Primary $PM_{2.5}$
- Secondary PM from NOx, SO_x, NH_3, VOC

Model for annual average $PM_{2.5}$

- All processes are annual-average: Transport, reaction rates, emissions, plume-rise, chemical transformation, removal

Source-oriented exposure assessment



Emissions → **Intake**

Intake Fraction

Sources vary immensely in ability to produce exposure.

Research agenda: elucidate emissions → exposure relationship

3 key factors: **Population, Proximity & Persistence**

Graphic: After Smith, 1993 and Marshall, 2006

Source-receptor matrix from InMAP

S ⟶ **R**

At source location (**S**)

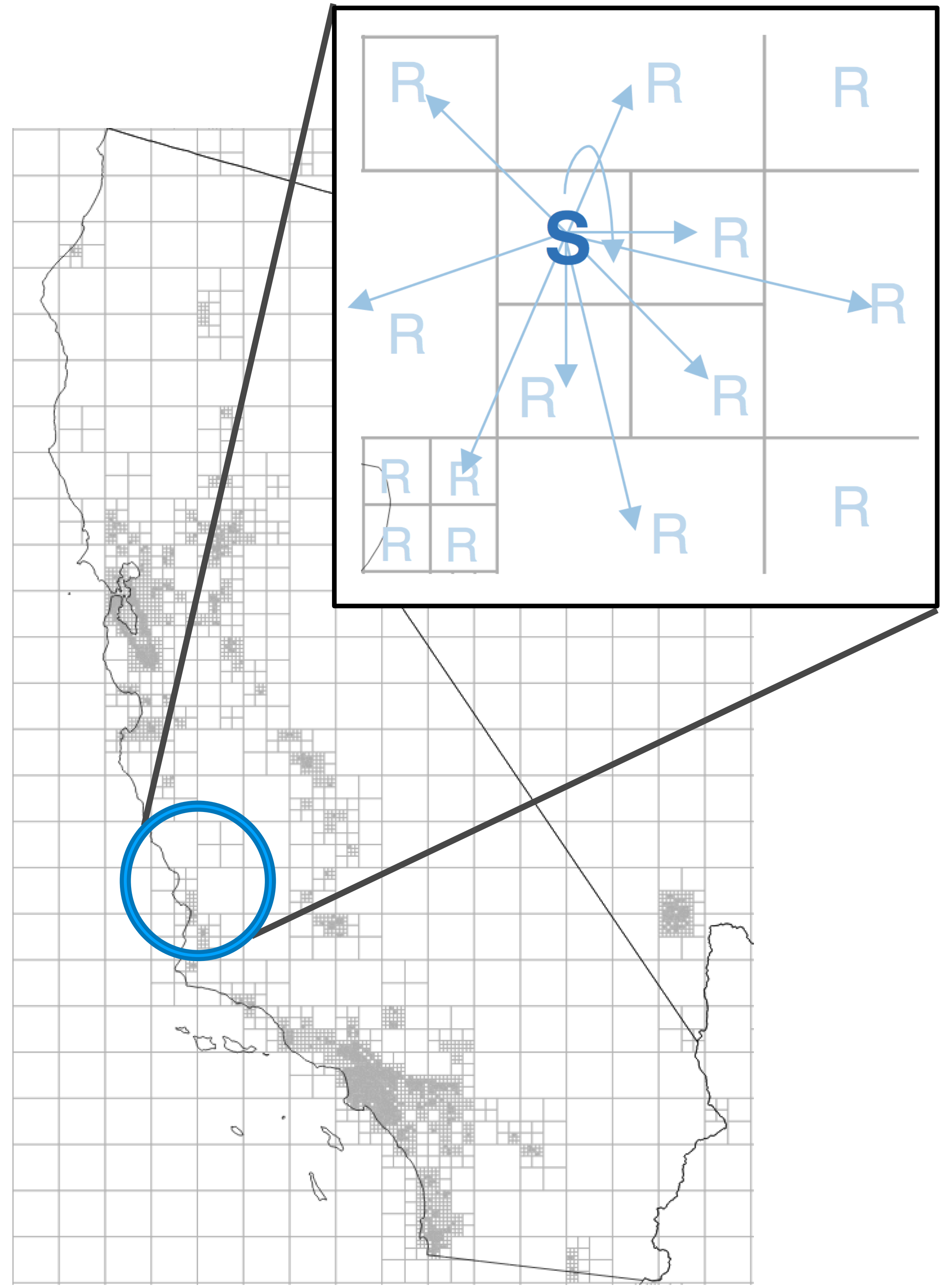
increase in annual emissions

of $PM_{2.5}$ and its precursors

leads to

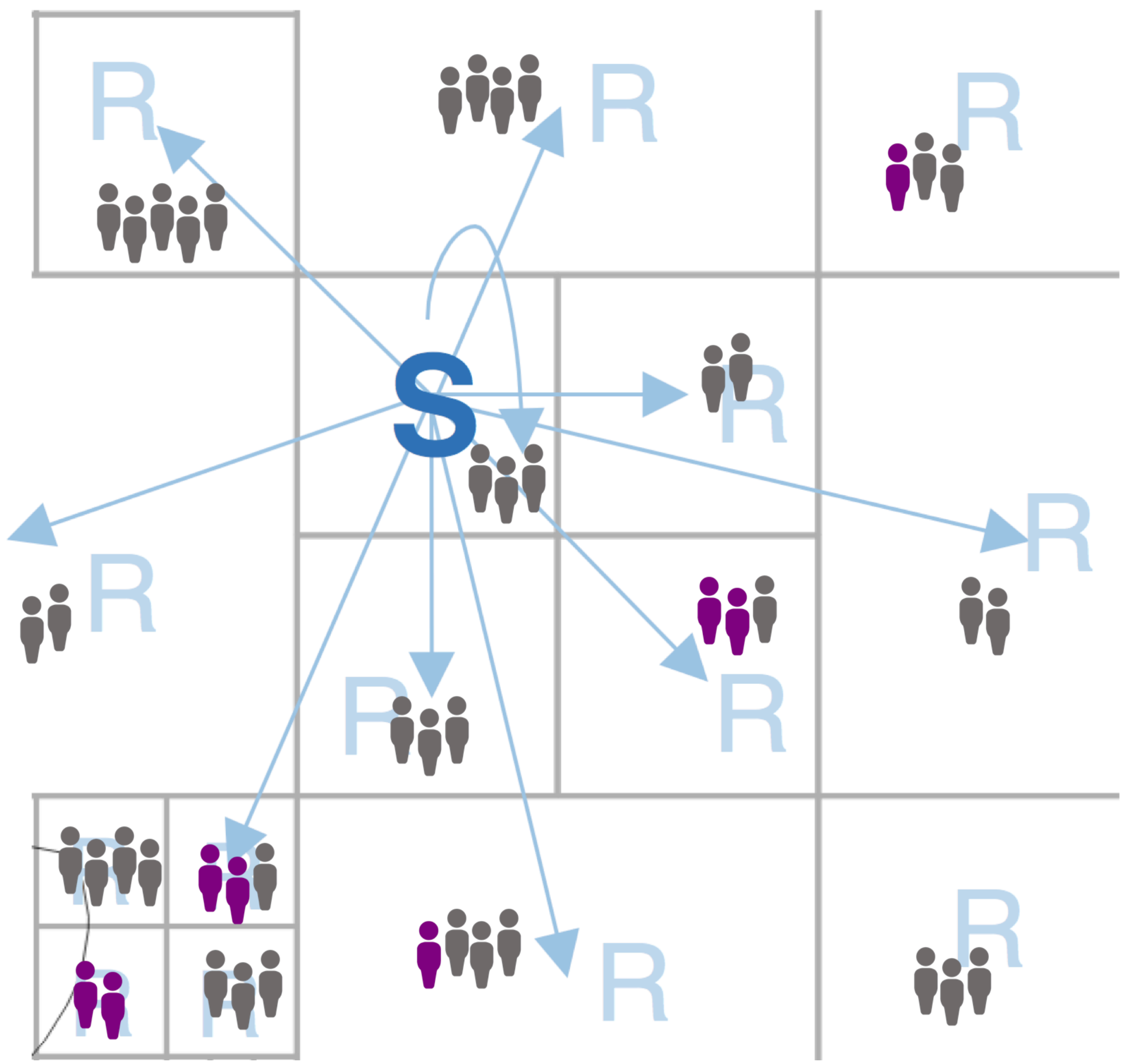
increase in annual average concentration of $PM_{2.5}$ at receptor location (**R**)

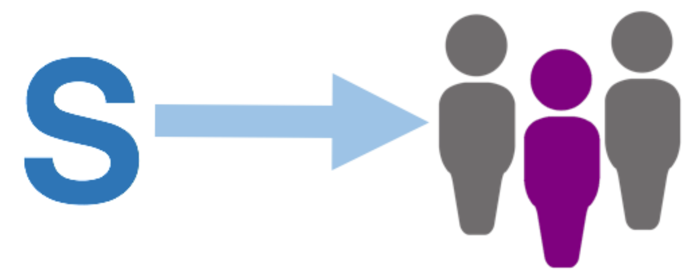
- The **S**→**R** relationship is calculated between all possible pairs of 21,180 InMAP grid cells
- ~ 4.5 million **S**→**R** pairs in California
- Includes **S**→**R** relationship of a cell with itself



Goodkind et al *PNAS* 2019

Source-oriented exposure assessment





Intake for single receptor:

($\Delta PM_{2.5}$ from ΔE at S)

× (population in R)

× (breathing rate)

Model effects at receptors (R), then trace them back to the source (S)

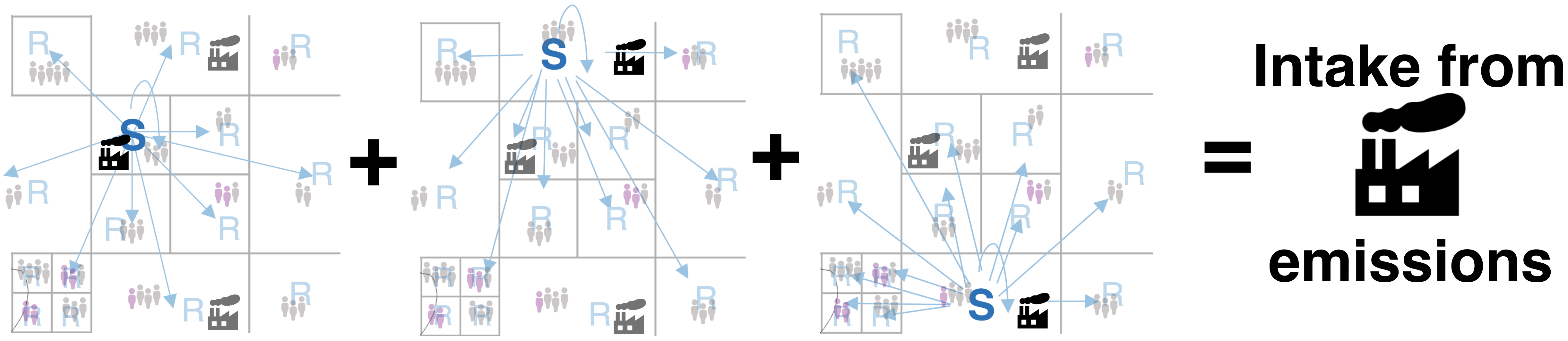
Source-oriented exposure metrics

Intake • The total amount of an air pollutant emitted by a specific source that is inhaled by the population per day • Proportional to population size • May be integrated over multiple pollutants	$\text{intake} = \sum_{i=1}^{n} C_i Q_i$ C_i, concentration (g m^{-3}) for person i n, number of people Q_i, breathing rate (m^3 d^{-1}) for person i	380 g d^{-1}
Intake fraction • The fraction of emissions from a specific source that are inhaled by the population • Proportional to population size • Specific to pollutant, location, and height	$iF = \frac{1}{E} \sum_{i=1}^{n} C_i Q_i$ C_i, concentration (g m^{-3}) for person i n, number of people Q_i, breathing rate (m^3 d^{-1}) for person i E, total emissions (g d^{-1})	15 ppm (g inhaled per tonne emitted)

Source-oriented EJ metrics

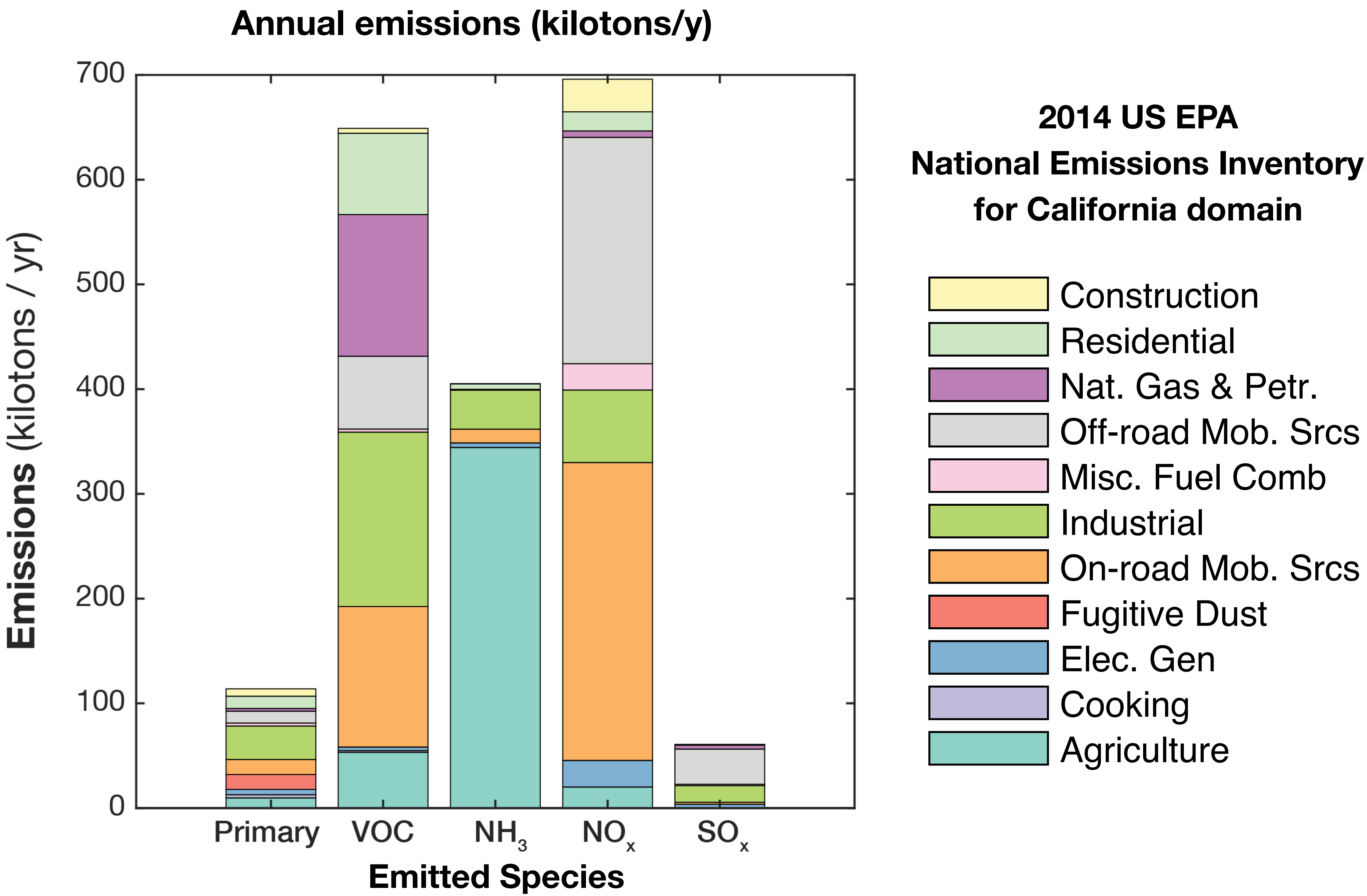
Relative Percent Difference (RPD) The percentage difference in $PM_{2.5}$ intake between the EJ-focused subpopulation and a comparison group	$RPD = \frac{\lvert \mu_{CG} - \mu_{VP} \rvert}{\mu}$ μ_{CG}, mean per-capita intake in comparison group μ_{VP}, mean per-capita intake in specified vulnerable population μ, population mean per-capita intake	25%
Intake Difference The absolute difference in $PM_{2.5}$ intake between the EJ-focused subpopulation and a comparison group	$\text{intake difference} = \sum_{i=1}^{n} C_{iG} Q_i - \sum_{i=1}^{n} C_{io} Q_i$ C_{iG}, C_{iO}, concentration (g m^{-3}) for person i within the group of interest (iG) or within the group of others (iO) n, number of people Q_i, breathing rate (m^3 d^{-1}) for person i, assumed equal across groups	380 g d^{-1}

Sector-specific summary metrics

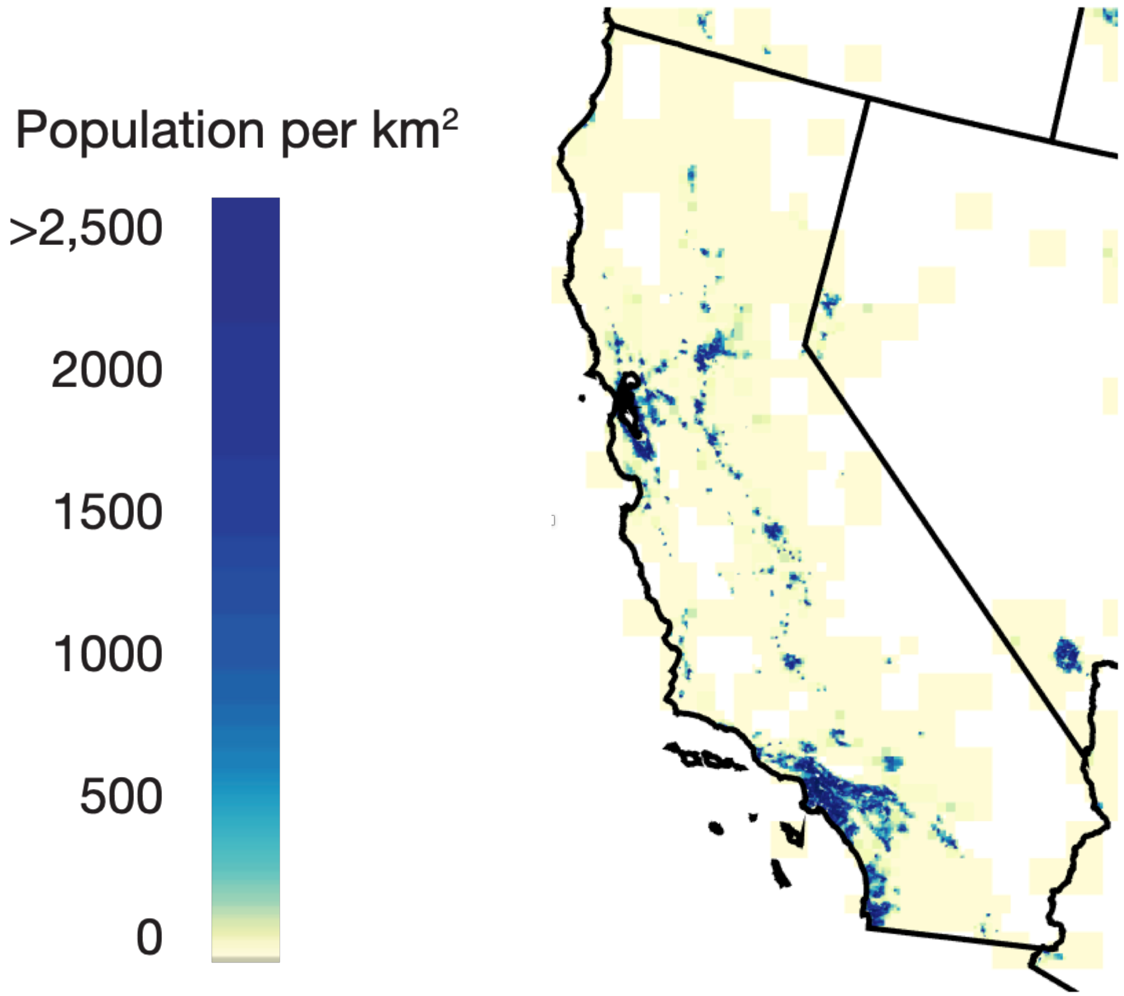


- The total intake from a source category is calculated by adding together the intake from emissions in that category at each source location (S)
- This calculation integrates emissions of different pollutant species and emissions at different plume heights into single intake value

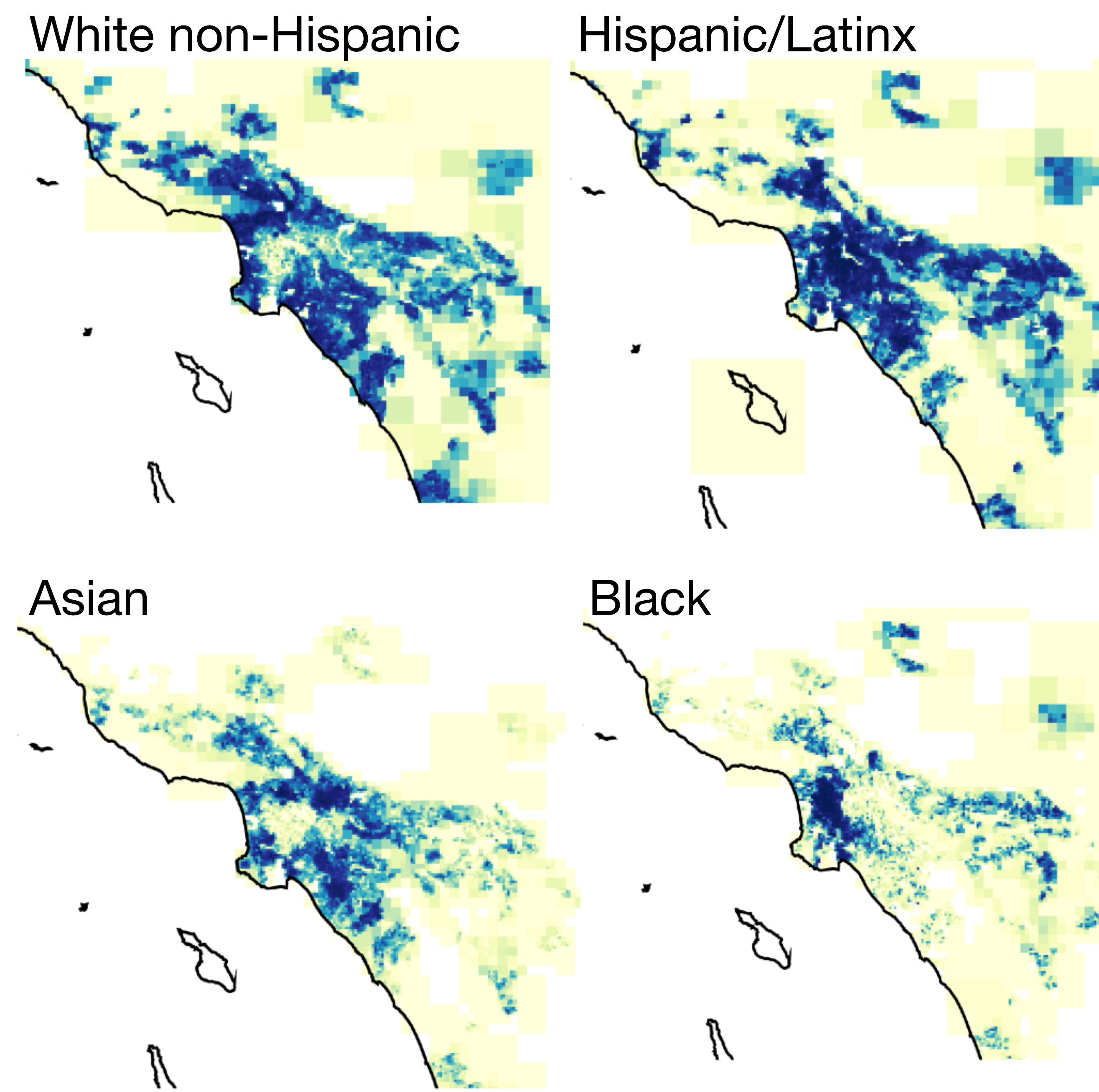
Emissions inventory and sector categories



Demographics in model domain



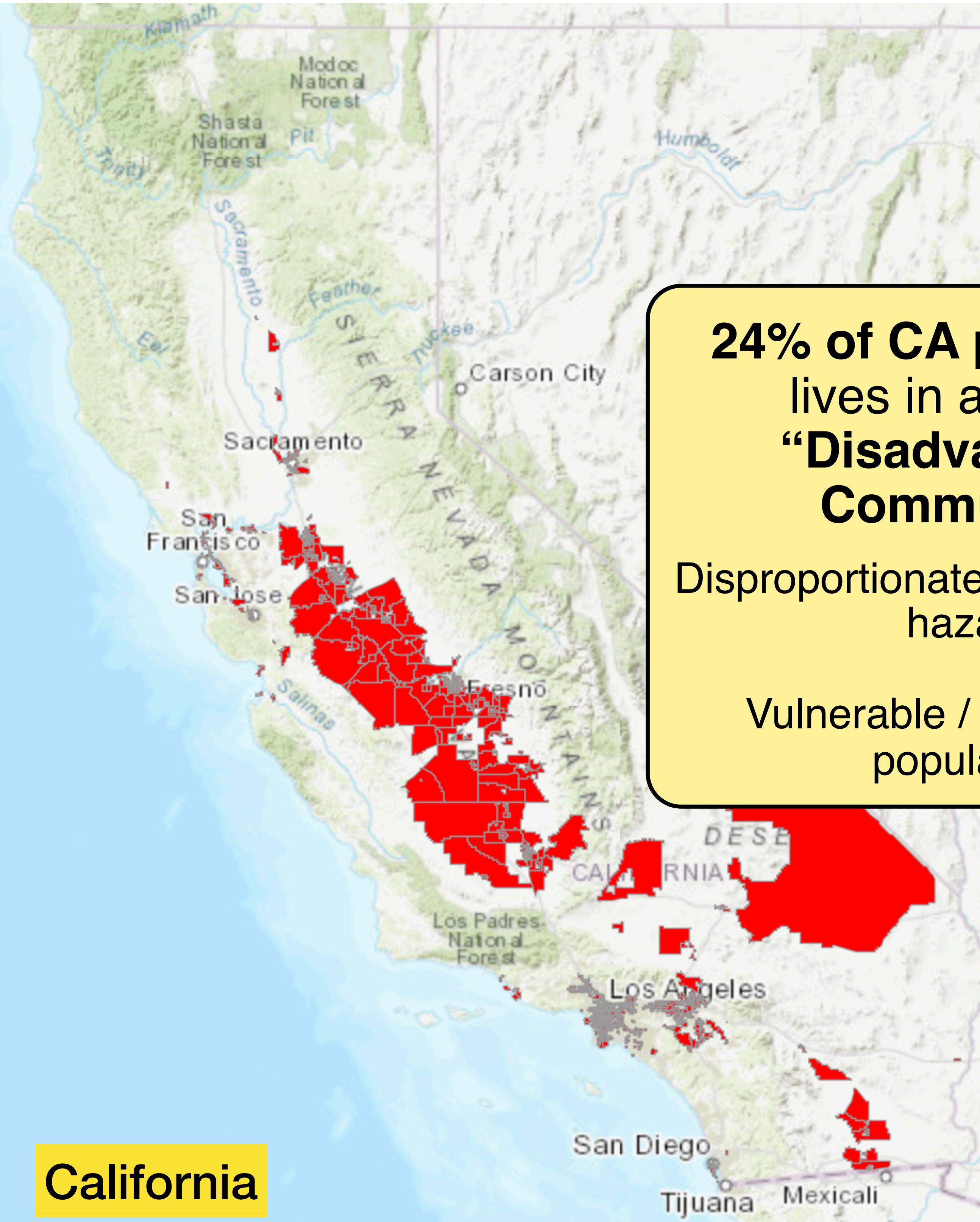
Example of differences in demographic patterns: Race in the Los Angeles area



	Population Size	%
White non-Hispanic	17,200,000	40%
Hispanic/Latinx	15,600,000	37%
Asian	5,500,000	13%
Black	2,400,000	6%
Multiracial/Other	1,700,000	4%

Population data from 2016 American Community Survey: 5-Year Data

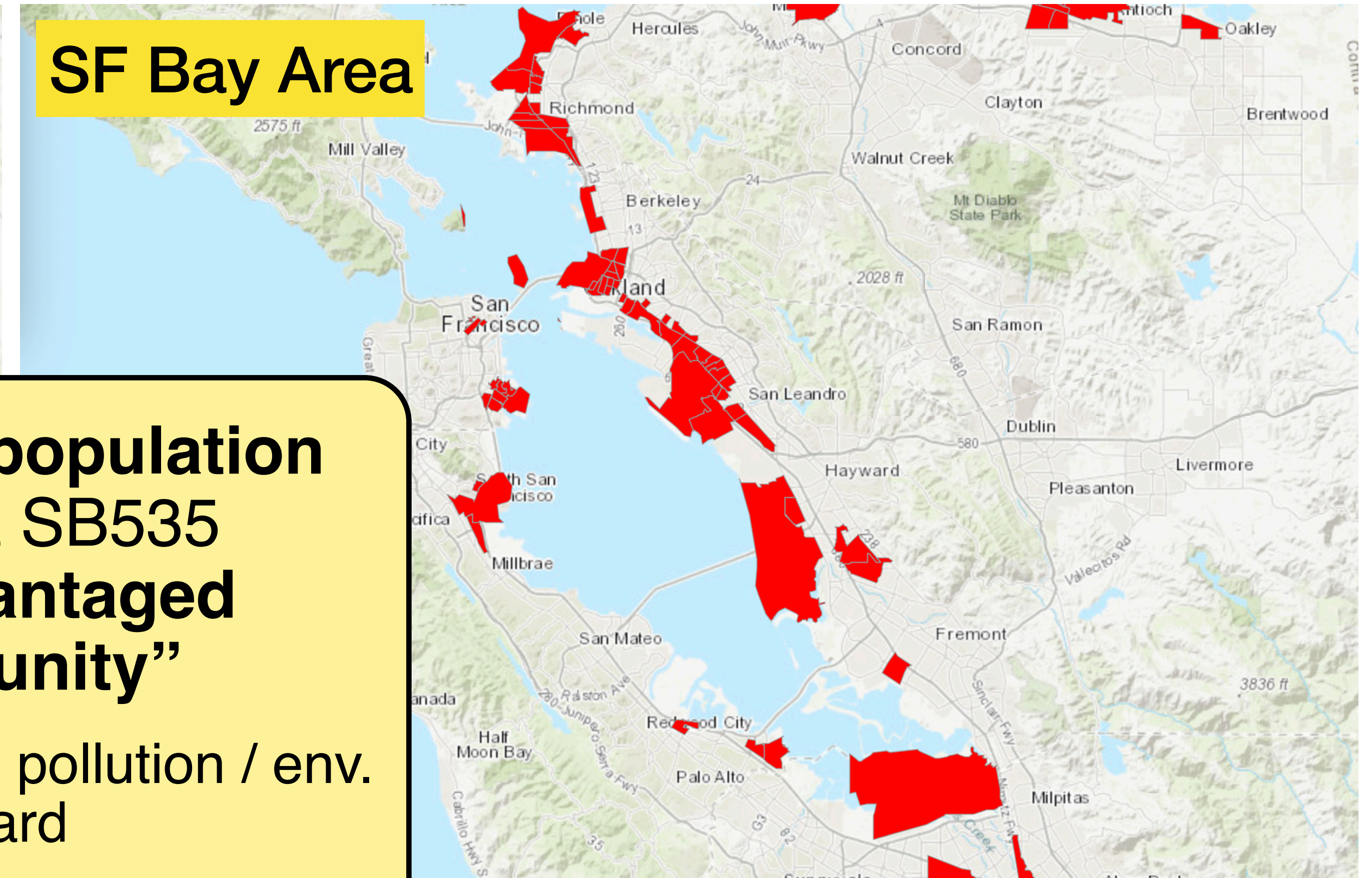
CA disadvantaged communities (DAC)

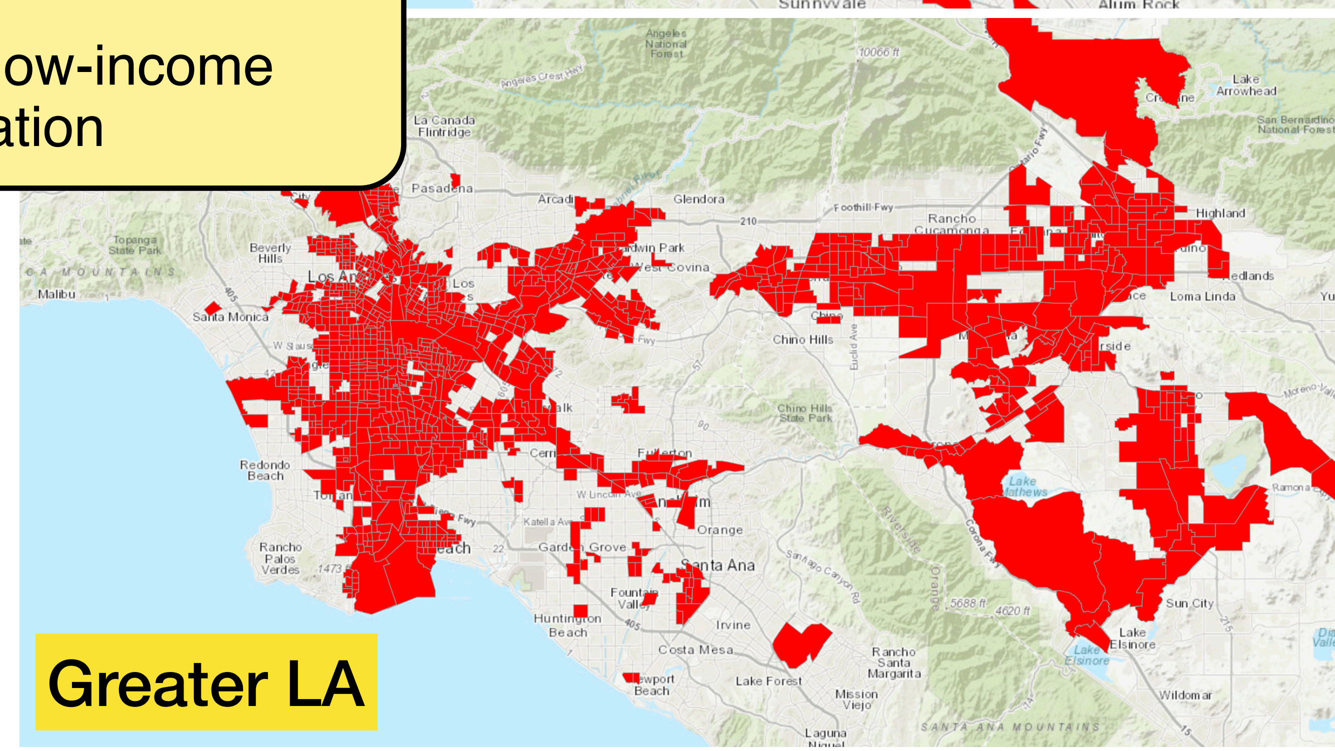


24% of CA population
lives in a SB535
"Disadvantaged Community"

Disproportionate pollution / env. hazard

Vulnerable / low-income population



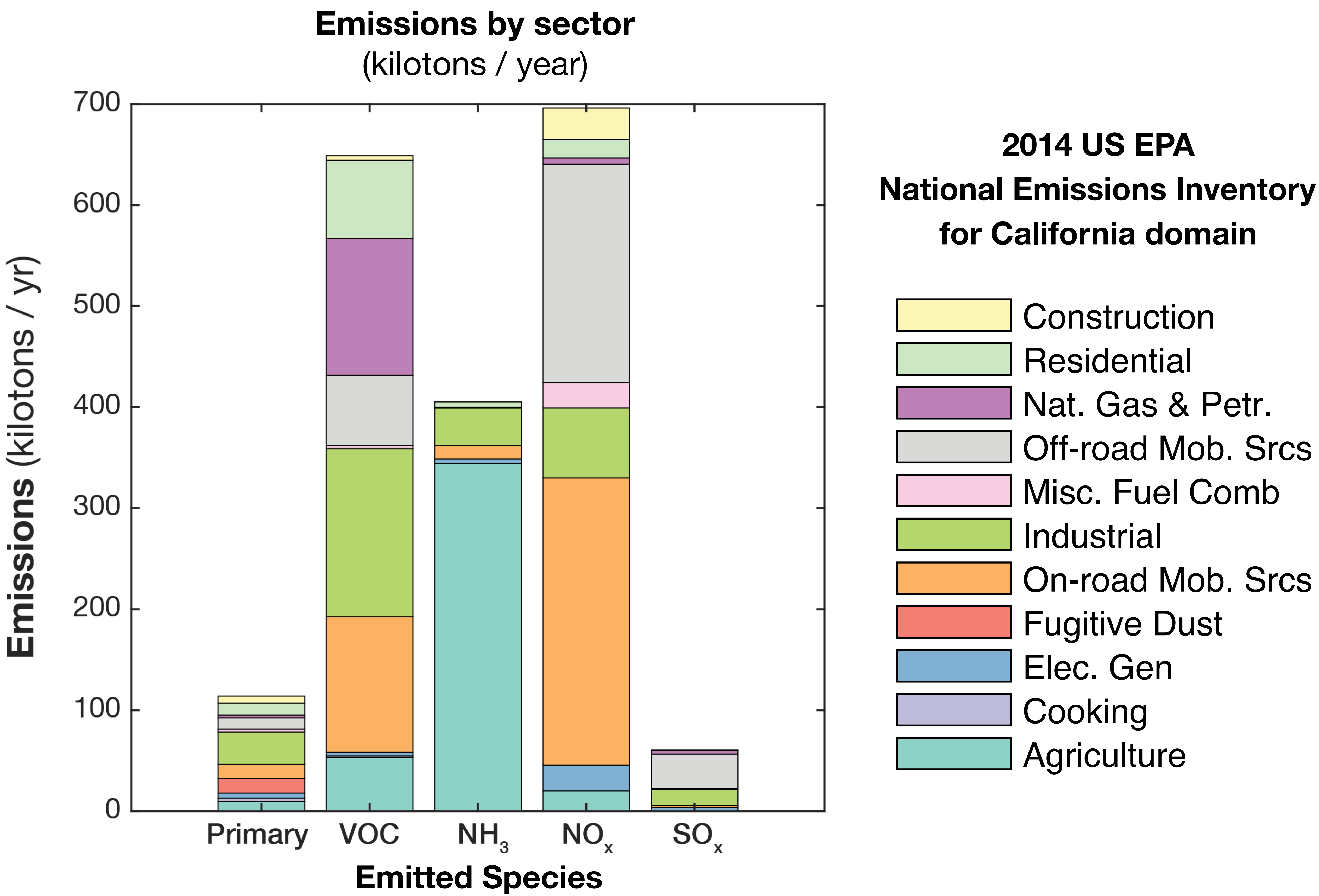


Limitations of this methodology

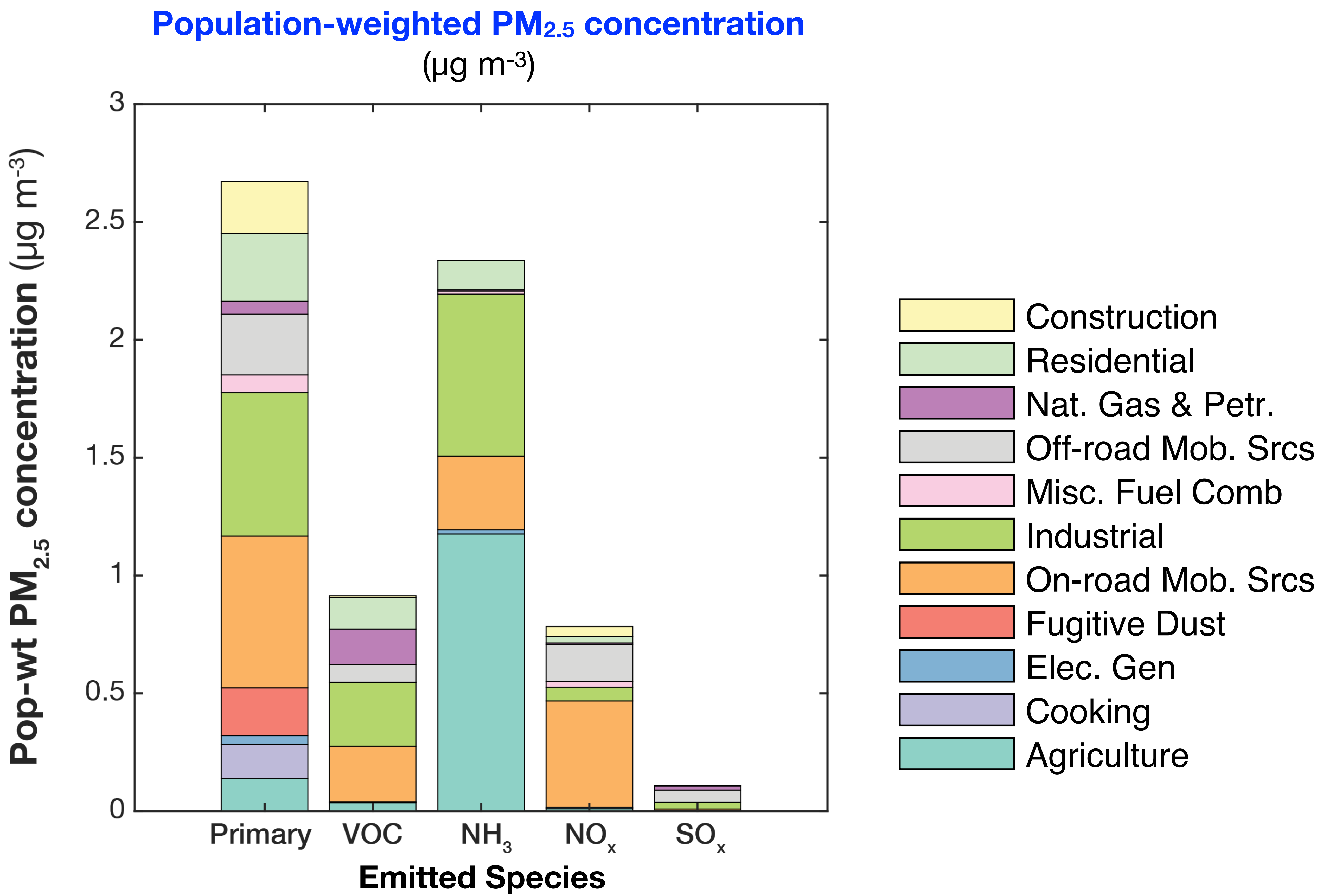
- This is a **screening tool**, not a substitute for more rigorous exposure modeling.
- **Model limitations**:
  - **Reduced-form model** with some inaccuracy.
  - Performs moderately well when evaluated against more complex models or monitoring data.
  - Only provides information on **annual-averages**.
  - **Key limitation: atmospheric chemistry** is based on 2005 NEI. The substantial reduction in NO_X and SO_X emissions leads to error in calculating concentrations and iF of secondary inorganics, with error most prominent in pNH_4.
    - We do not emphasize results for the agricultural sector. Nearly all intake derives from livestock NH_3 emissions.
- **Exposure limitations:**
  - Based on census residential patterns. Does not account for activity patterns.
  - Outdoor concentrations, does not account for differential infiltration rates in different building types.
  - Uniform breathing rate, over time and over different groups.

Key Findings

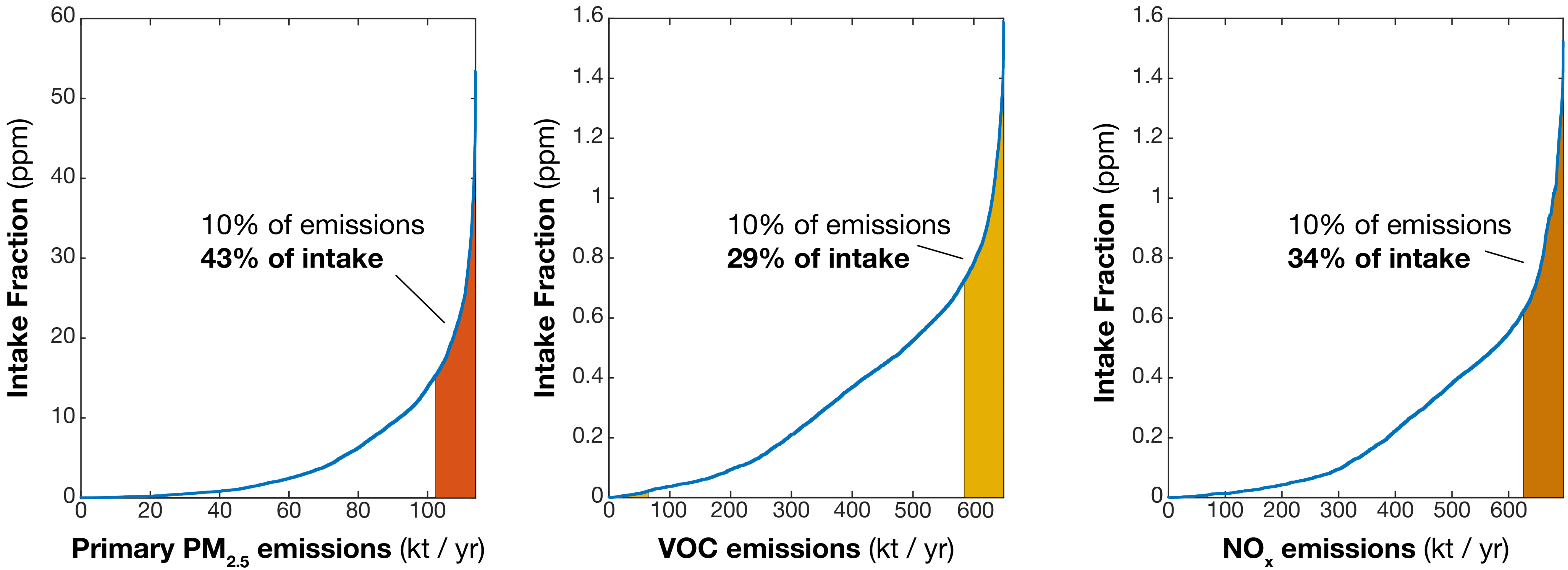
Concentration ≠ Emissions



Concentration ≠ Emissions



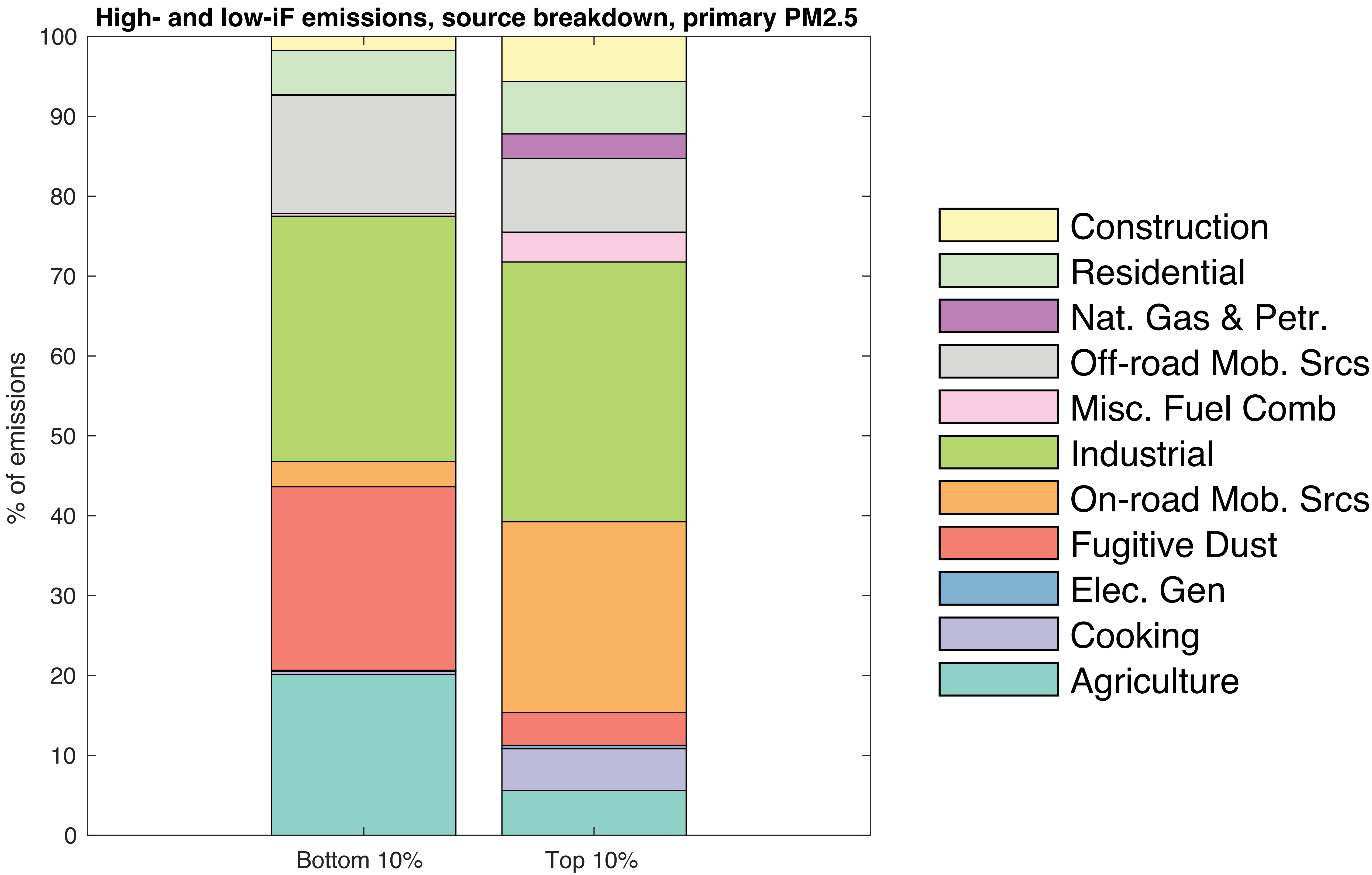
Intake = emissions × intake fraction



Sources with high iF result in disproportionately high intake.

Top 10% of emissions of each $PM_{2.5}$ component → 48% of CA intake.

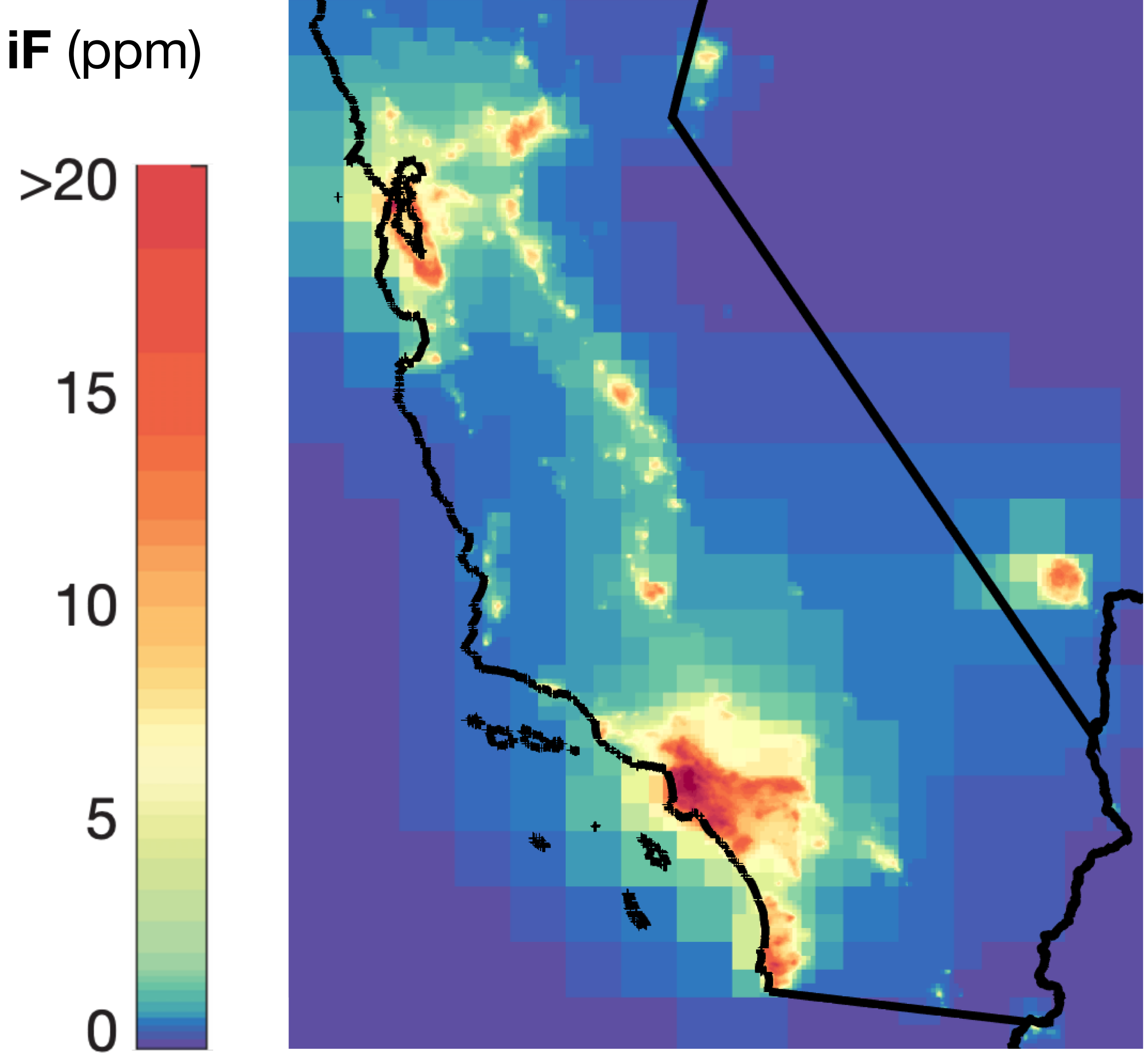
iF varies by sector



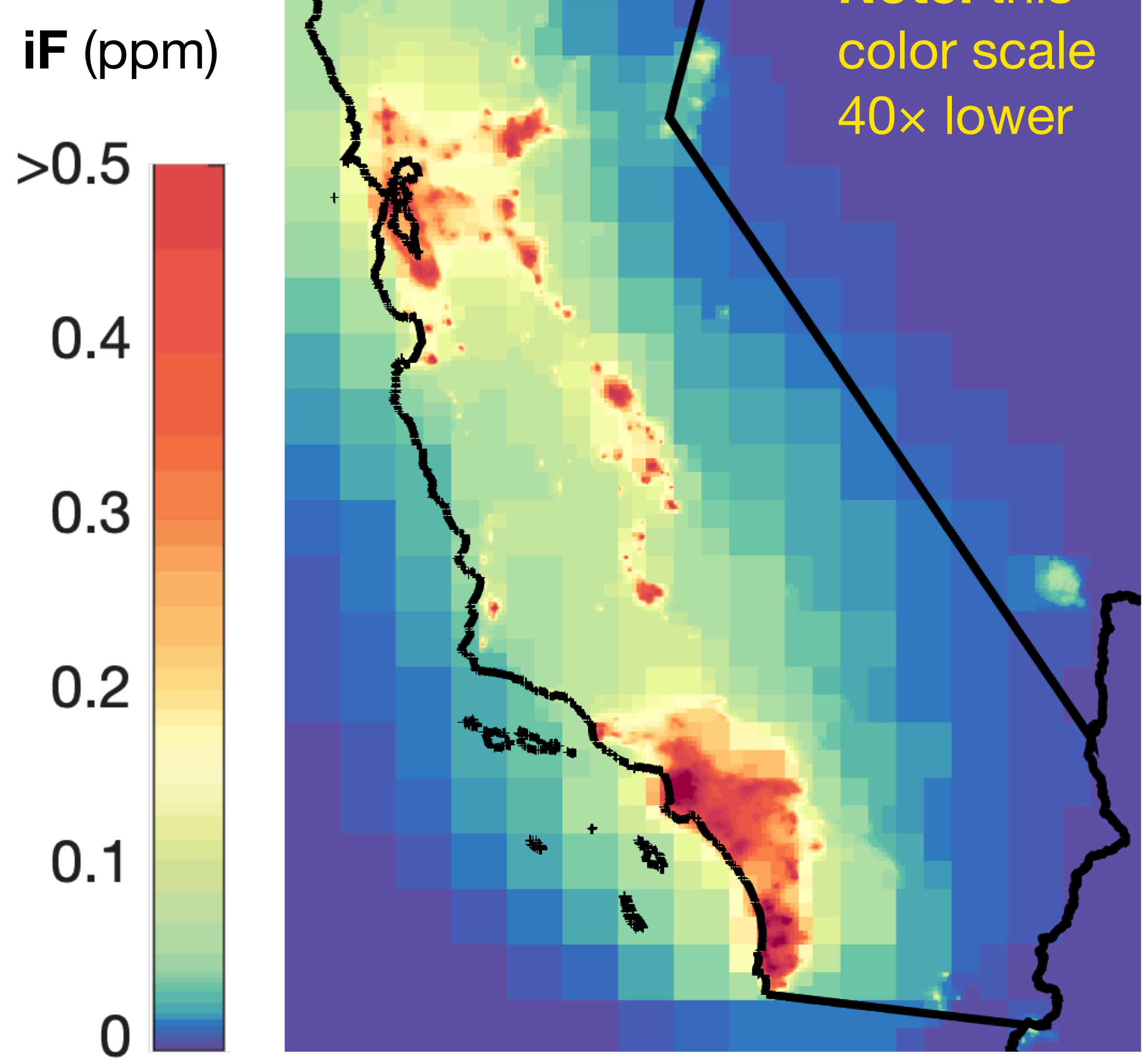
Example iF maps: total population

Ground level emissions

Primary $PM_{2.5}$



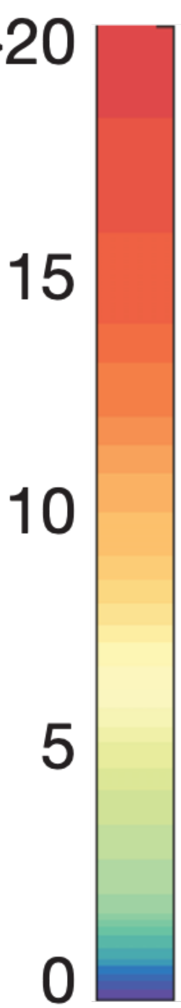
Secondary nitrate $PM_{2.5}$ from NO_x



Example iF maps: total population

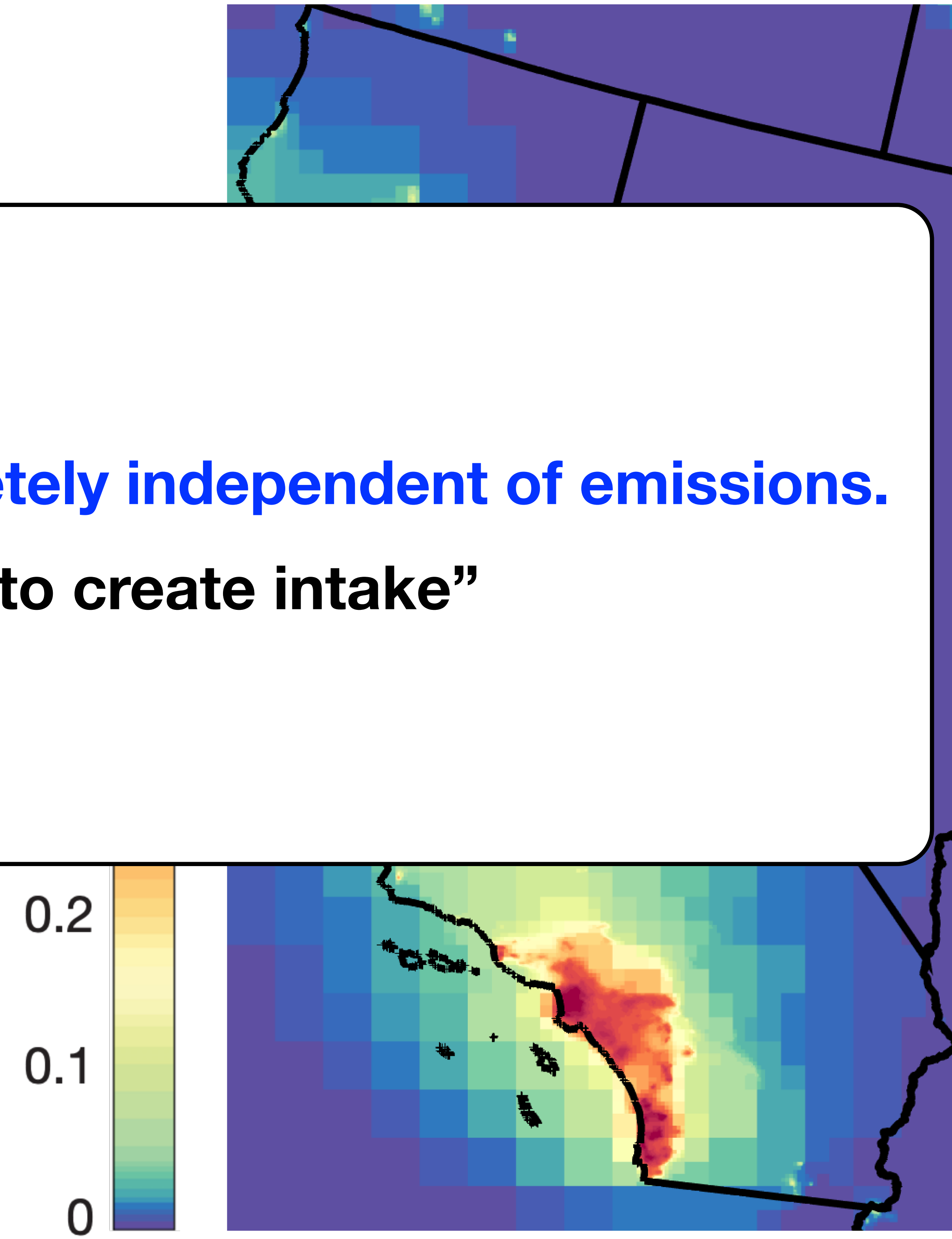
Ground level emissions

iF (ppm)



Primary $PM_{2.5}$

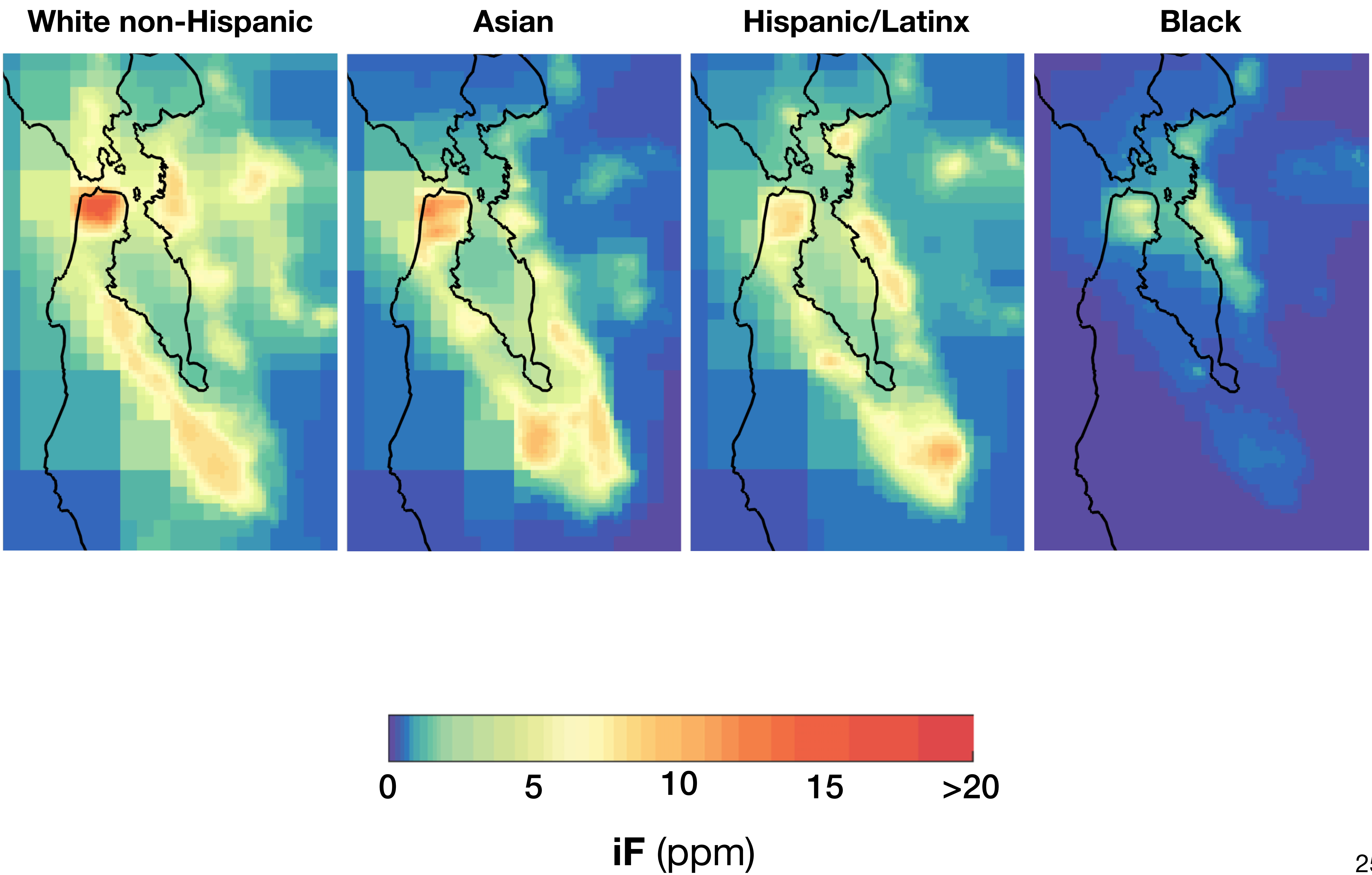
Secondary nitrate $PM_{2.5}$ from NO_x



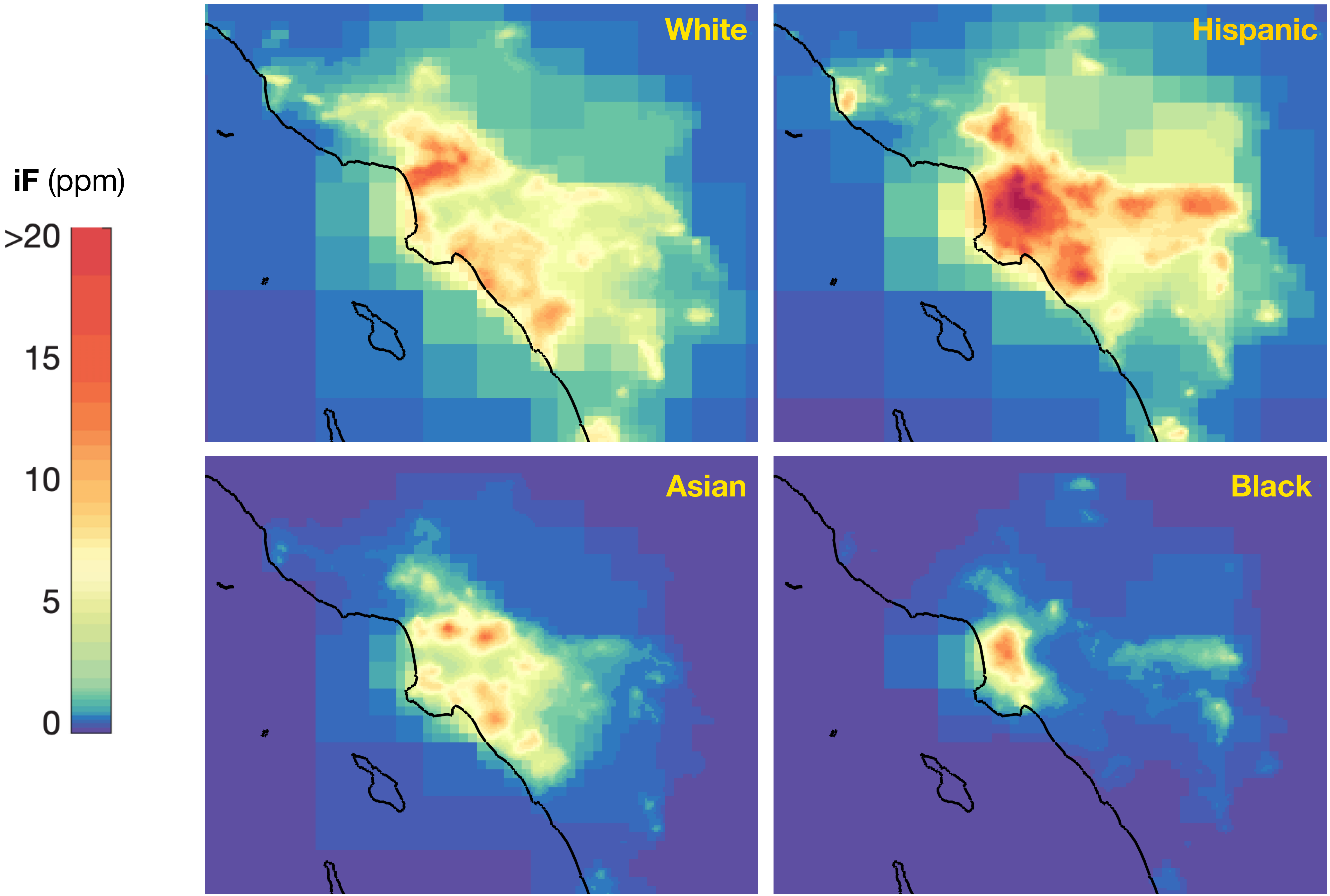
Intake fraction is completely independent of emissions.

“Potential to create intake”

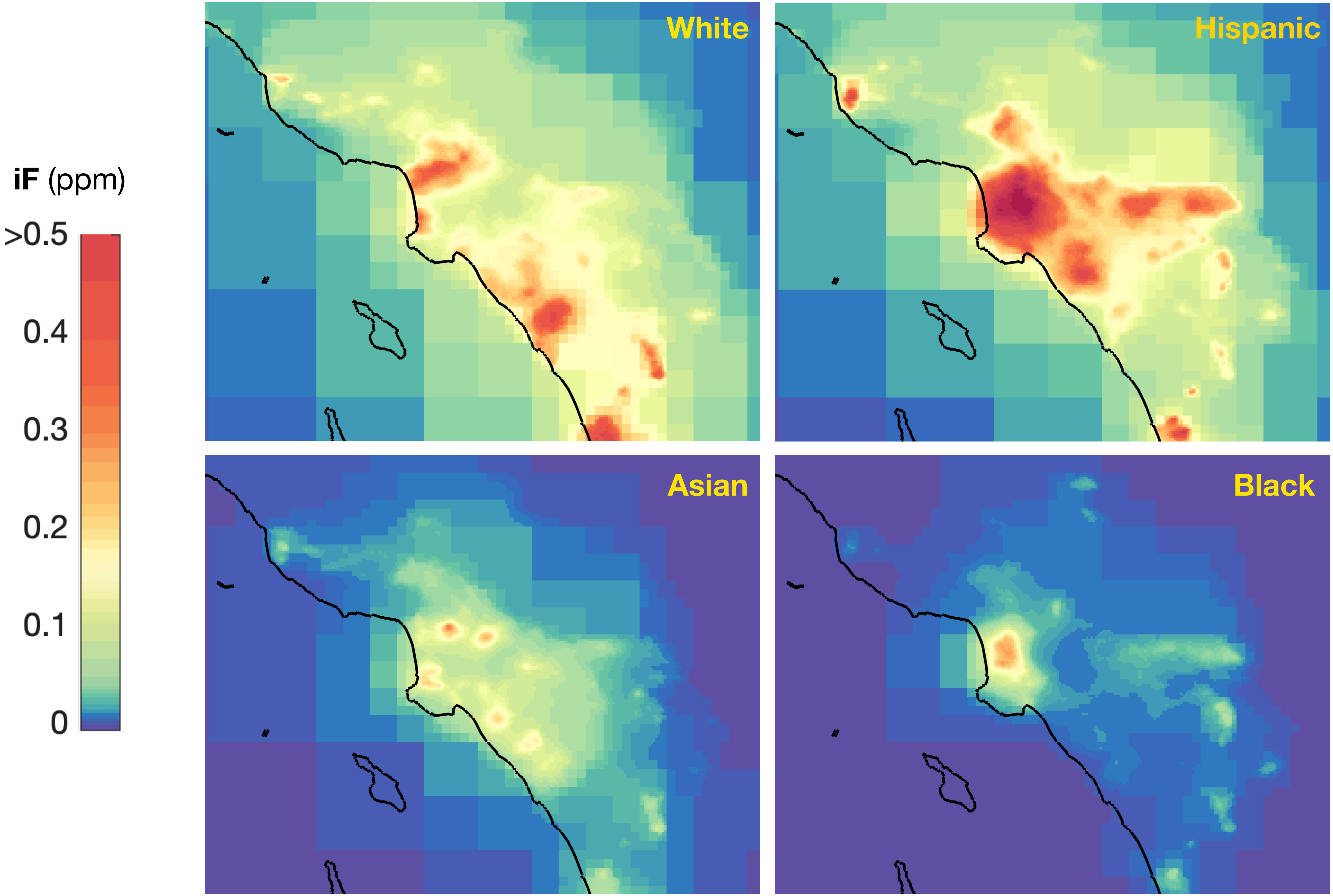
Primary $PM_{2.5}$ iF maps: by race



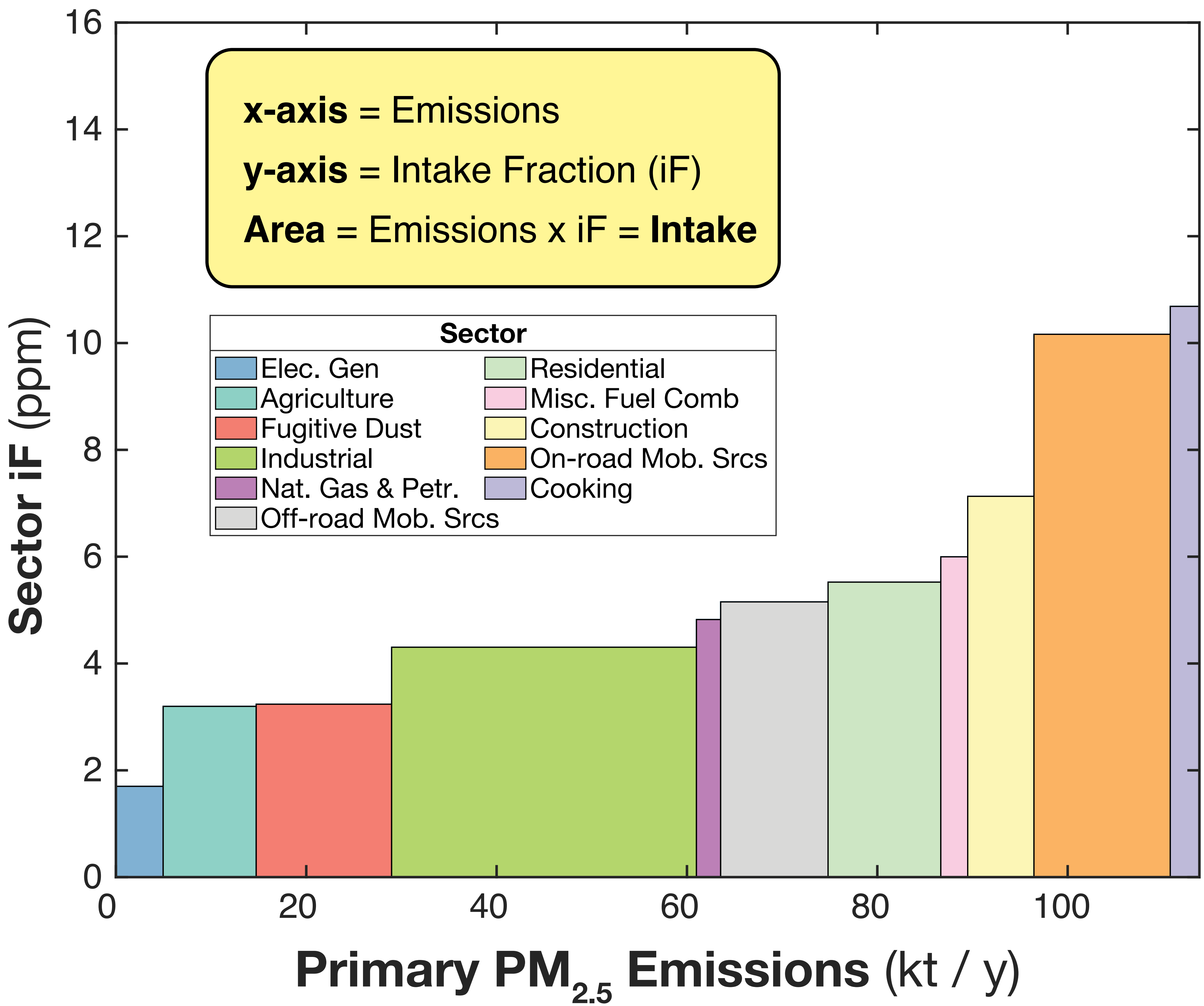
Primary $PM_{2.5}$ iF maps: by race



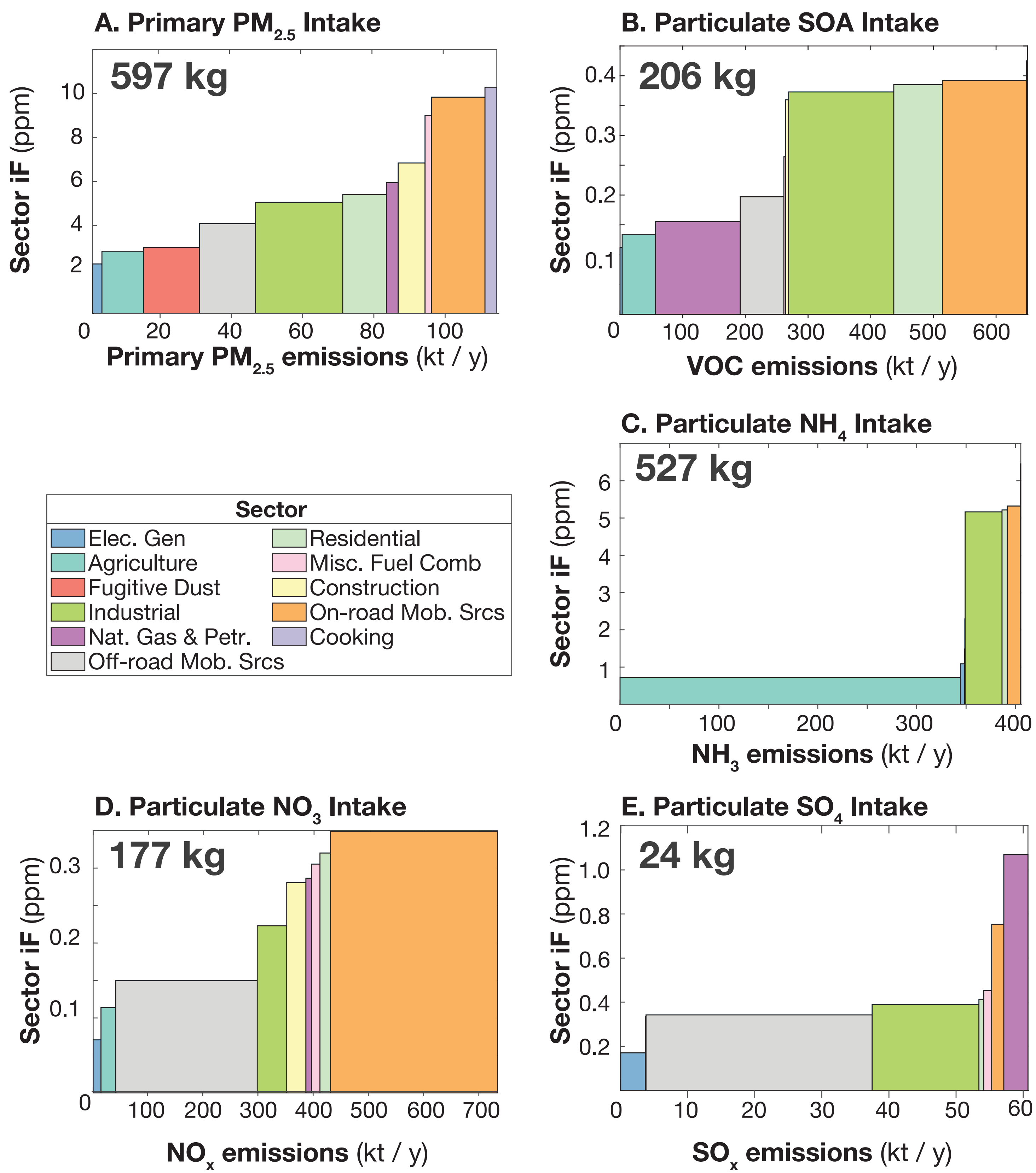
Particulate NO_3 iF maps: by race



Primary $PM_{2.5}$ intake and iF by sector



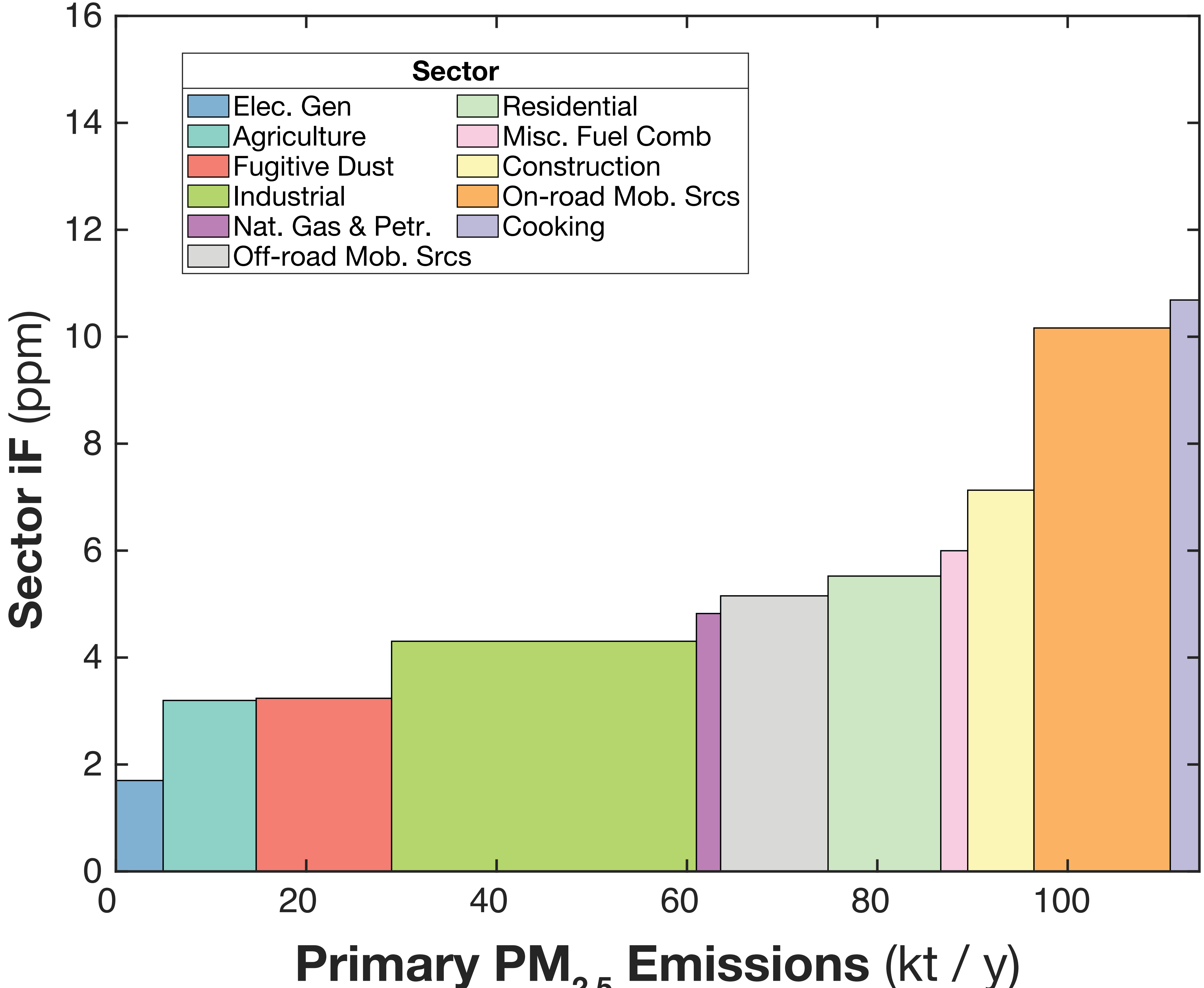
Intake and intake fraction by sector



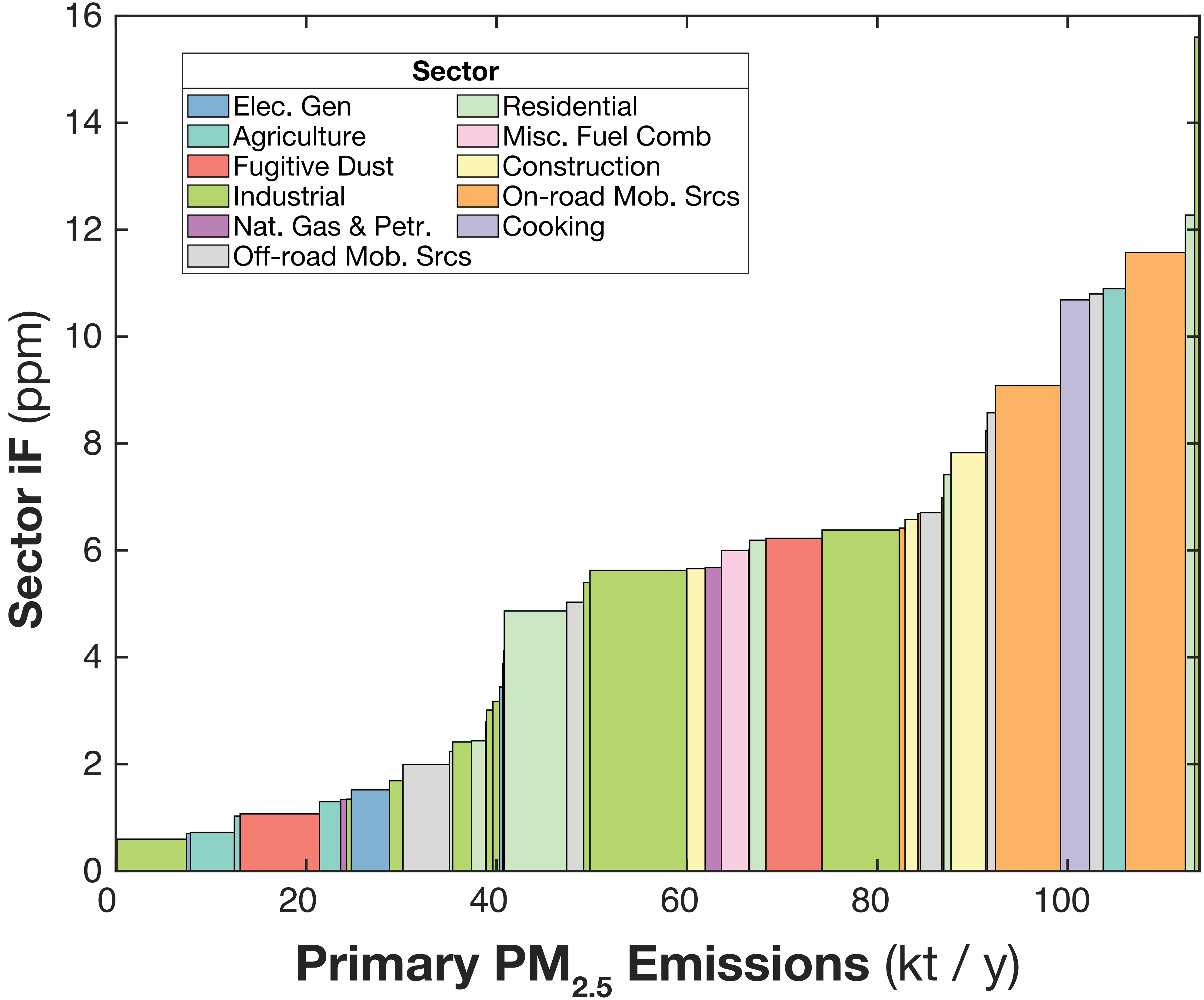
High impact strategies may target sectors with **high emissions and high iF.**

Examples:
On-road mobile sources
Industry

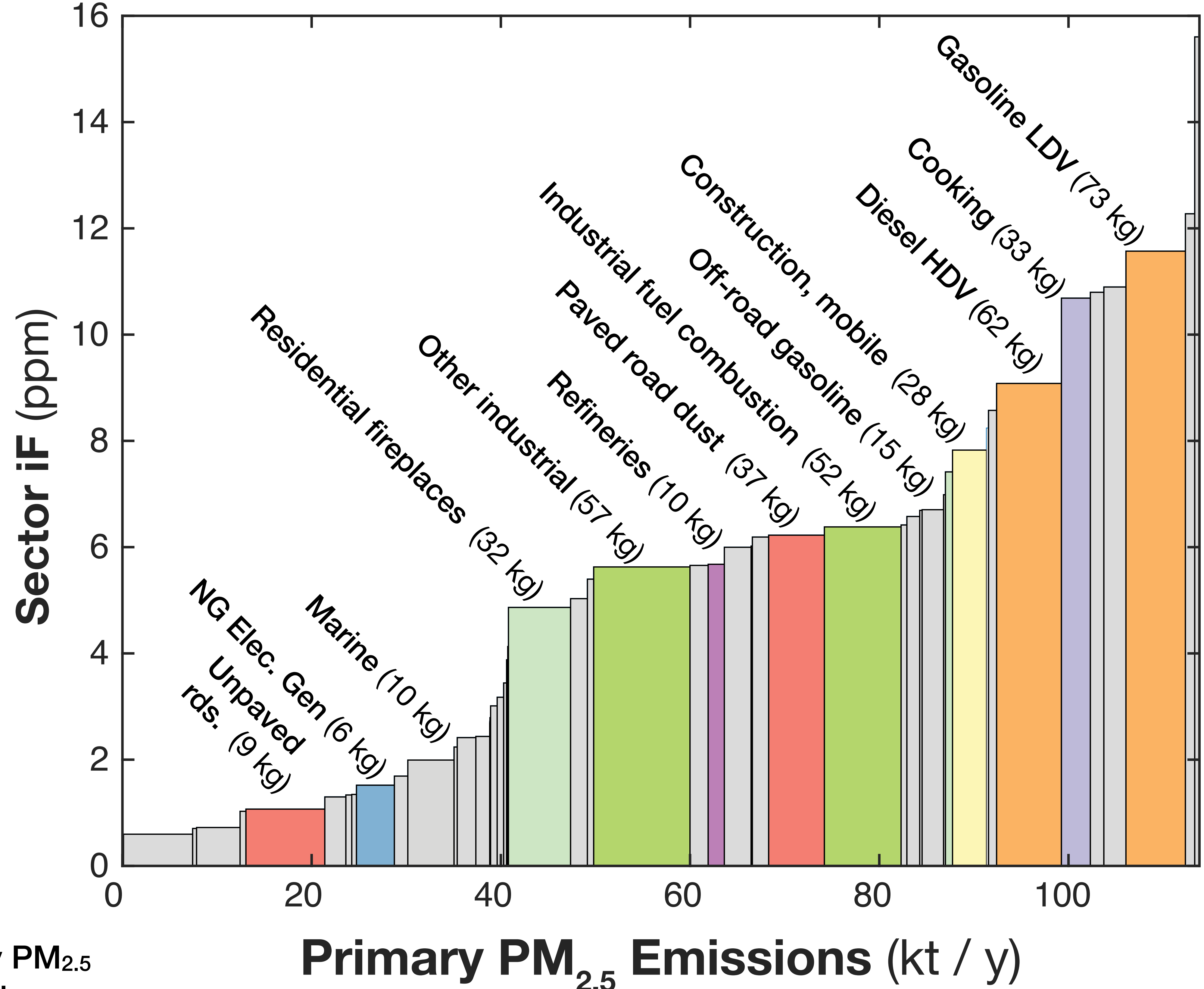
Primary $PM_{2.5}$ intake by sector



Primary $PM_{2.5}$ intake by subsector

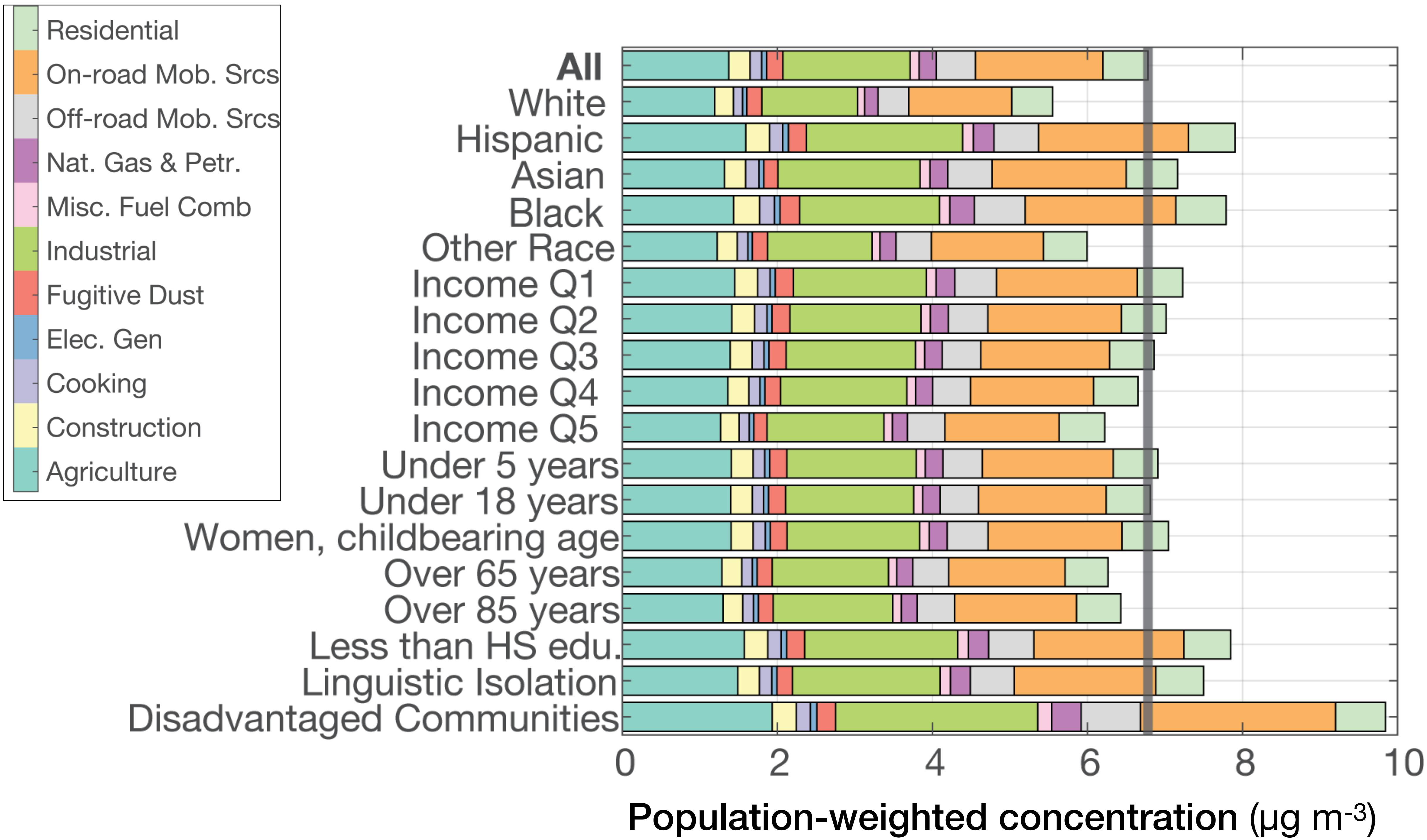


Primary $PM_{2.5}$ intake by subsector



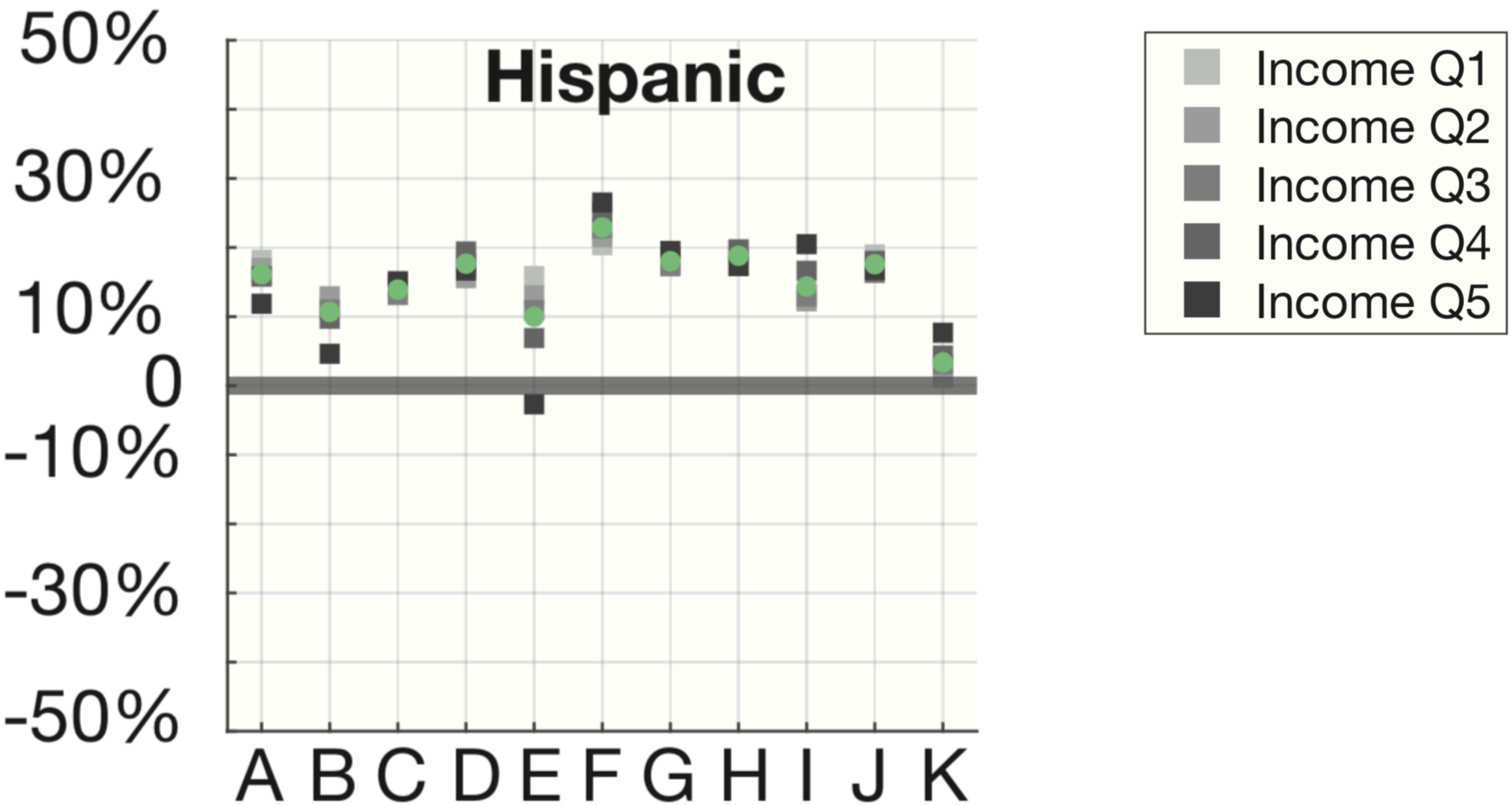
Total primary $PM_{2.5}$ intake = 597 kg

Disparity in pop-wt concentrations



Disadvantaged communities experience 45% higher $PM_{2.5}$ concentrations. **All major source categories contribute to disparity.**

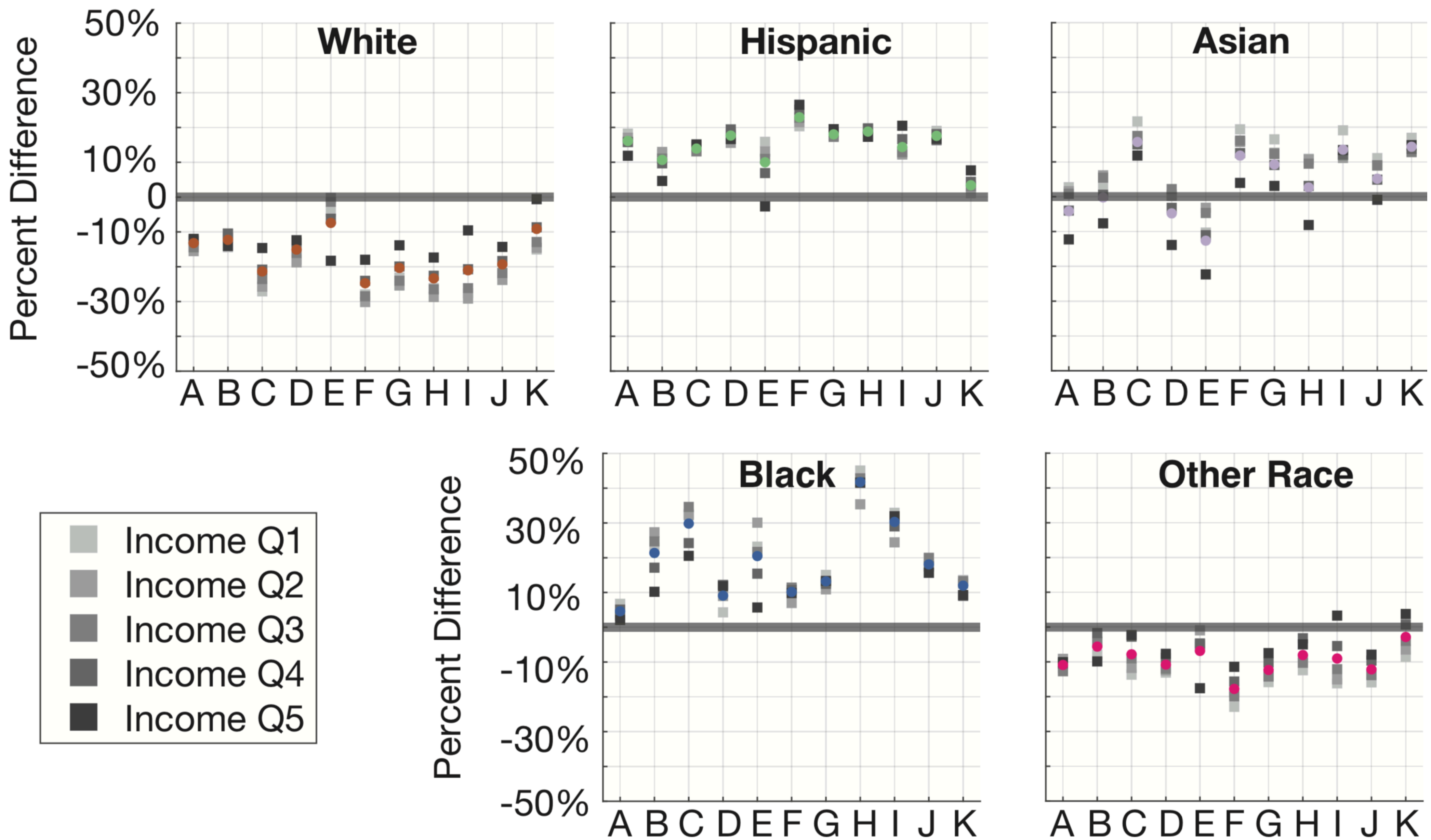
Disparity by race/ethnicity greater than income



Source Categories

A. Agriculture
B. Construction
C. Commercial Cooking
D. Electricity Generation
E. Fugitive Dust
F. Industrial
G. Misc. Fuel Combustion
H. Natural Gas & Petroleum
I. Off-Road Mobile Sources
J. On-Road Mobile Sources
K. Residential Sources (Outdoor Air)

Disparity by race/ethnicity greater than income



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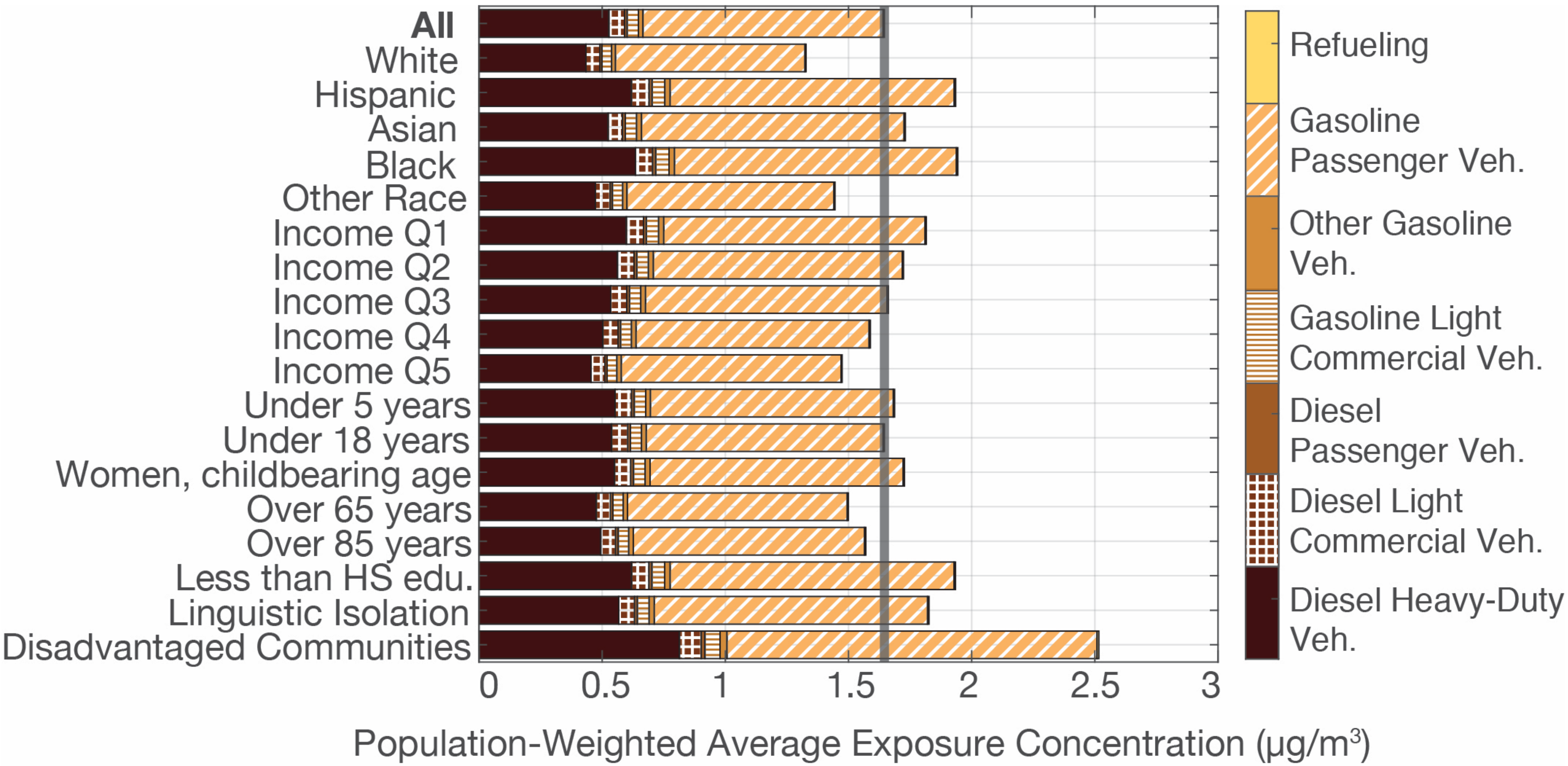
J. On-Road Mobile Sources
K. Residential Sources (Outdoor Air)

Focus sector: on-road mobile sources



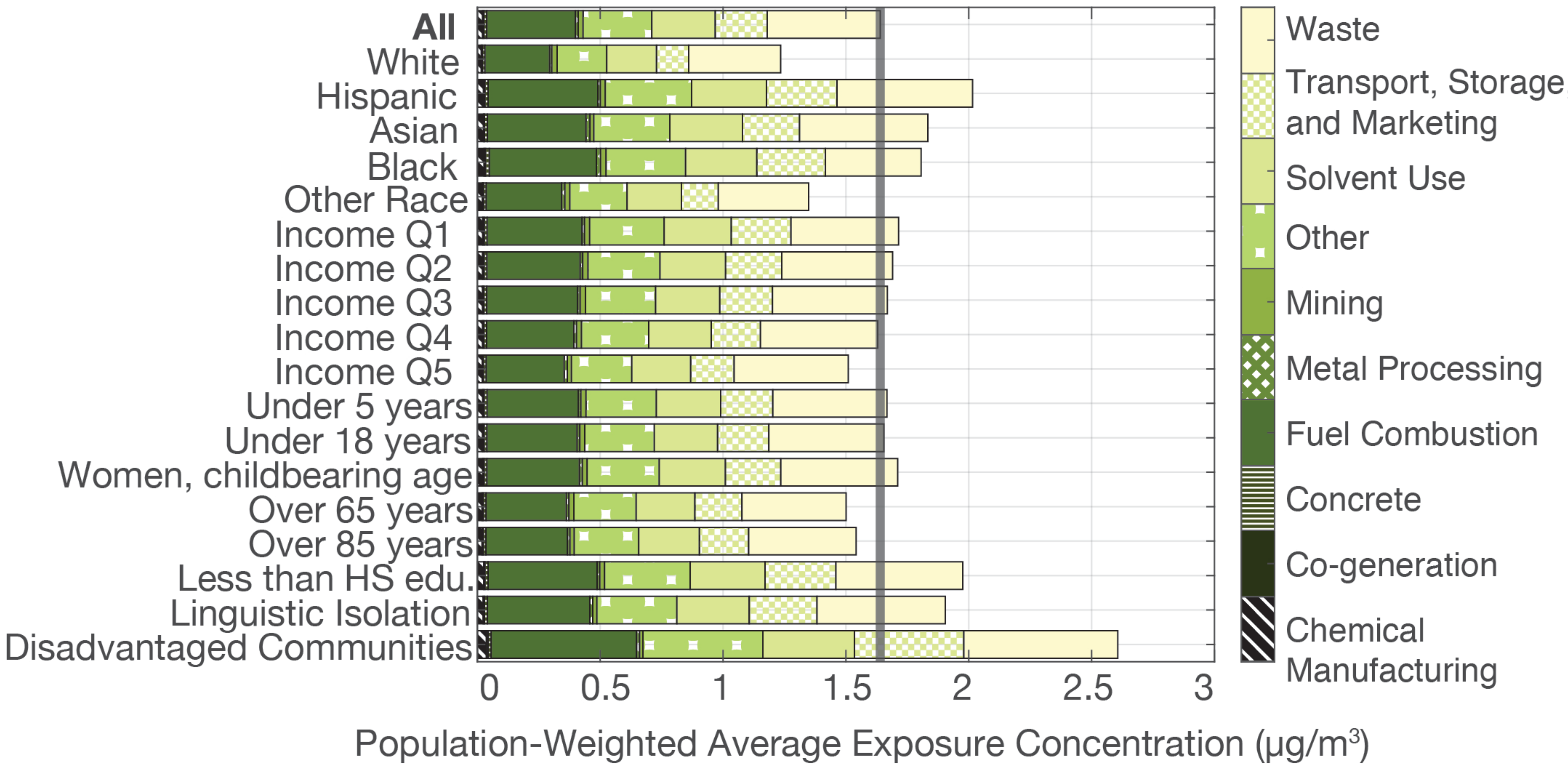
Net sector disparity in DACs: 0.9 µg m^{-3} $PM_{2.5}$.
Relative disparity: 53%

Largest contributions to disparity:

- Gasoline on-road: 0.53 µg m^{-3}
- Diesel-on-road: 0.29 µg m^{-3}

	Average	Total Δ for DACs (µg/m^3)	Relative Δ for DACs
Diesel HDV	0.53	0.29	54%
Diesel LCV	0.06	0.03	40%
Diesel Passenger	0.01	0.00	43%
Gasoline LCV	0.05	0.02	35%
Gasoline HDV	0.02	0.01	48%
Gasoline Passenger	0.97	0.53	54%
Refueling	0.01	0.00	39%
Total	1.65	0.87	53%

Focus sector: industrial sources



Net sector disparity in DACs: **1.0 μg m^{-3} $PM_{2.5}$.**

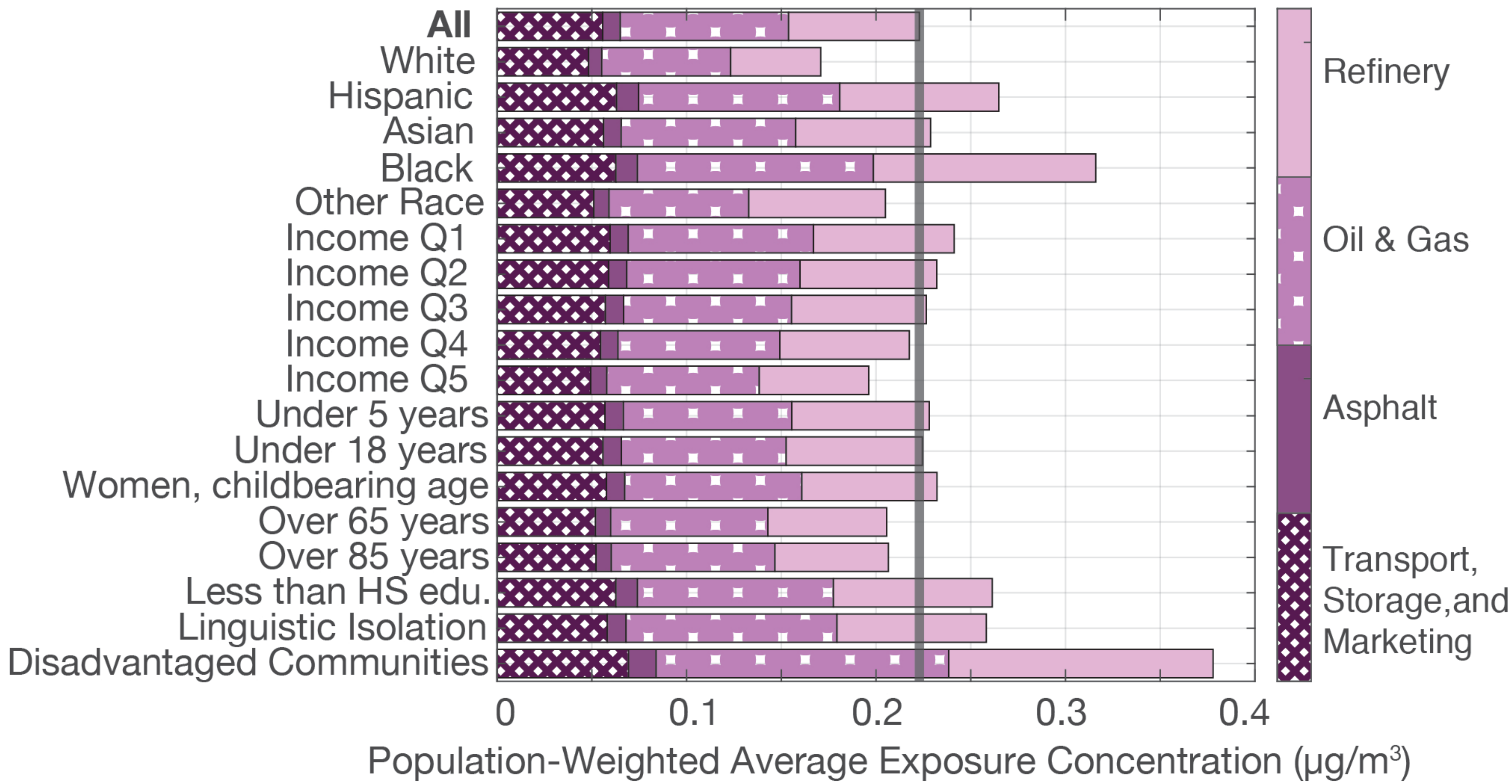
Relative disparity: **59%**

Largest contributions to disparity:

- Materials storage/transport: 0.23 μg m^{-3} **(+111%)**
- Industrial fuel combustion: 0.23 μg m^{-3}
- Waste disposal and incineration: 0.17 μg m^{-3}

	Average	Total Δ for DACs (μg/m^3)	Relative Δ for DACs
Chemical Manufacturing	0.02	0.02	71%
Cogeneration	0.01	0.00	47%
Concrete and Cement	0.01	0.00	3%
Fuel Combustion	0.36	0.23	64%
Waste Disposal & Incin.	0.46	0.17	36%
Metals Processing	0.01	0.00	15%
Surface Mining	0.02	-0.01	-34%
Other	0.28	0.21	75%
Solvent Utilization	0.26	0.11	44%
Storage and Transport	0.21	0.23	111%
Total	1.64	0.97	59%

Focus sector: nat. gas and petroleum



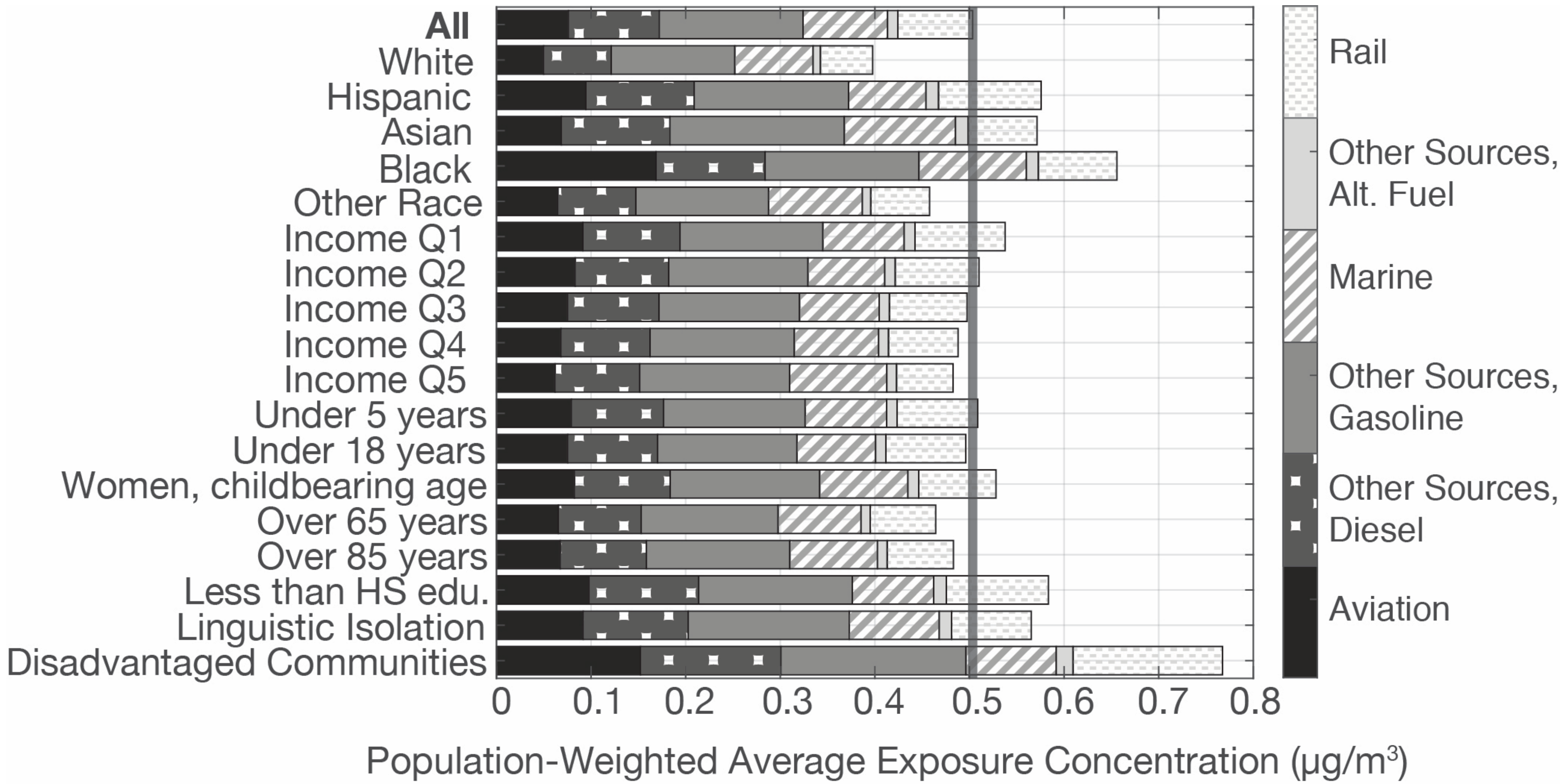
Net sector disparity in DACs: 0.2 μg m^{-3} PM$_{2.5}$.
High relative disparity: 70%

	Average	Total Δ for DACs (μg/m^3)	Relative Δ for DACs
Asphalt Manufact.	0.01	0.01	57%
Oil & Gas Production	0.09	0.07	74%
Petroleum Refining	0.07	0.07	102%
Petroleum TSM	0.06	0.01	24%
Total	0.22	0.16	70%

Largest contributions to disparity:

- Petroleum refining: 0.07 μg m^{-3} **(+102%)**
- Oil and gas production: 0.07 μg m^{-3}

Focus sector: off-road mobile sources



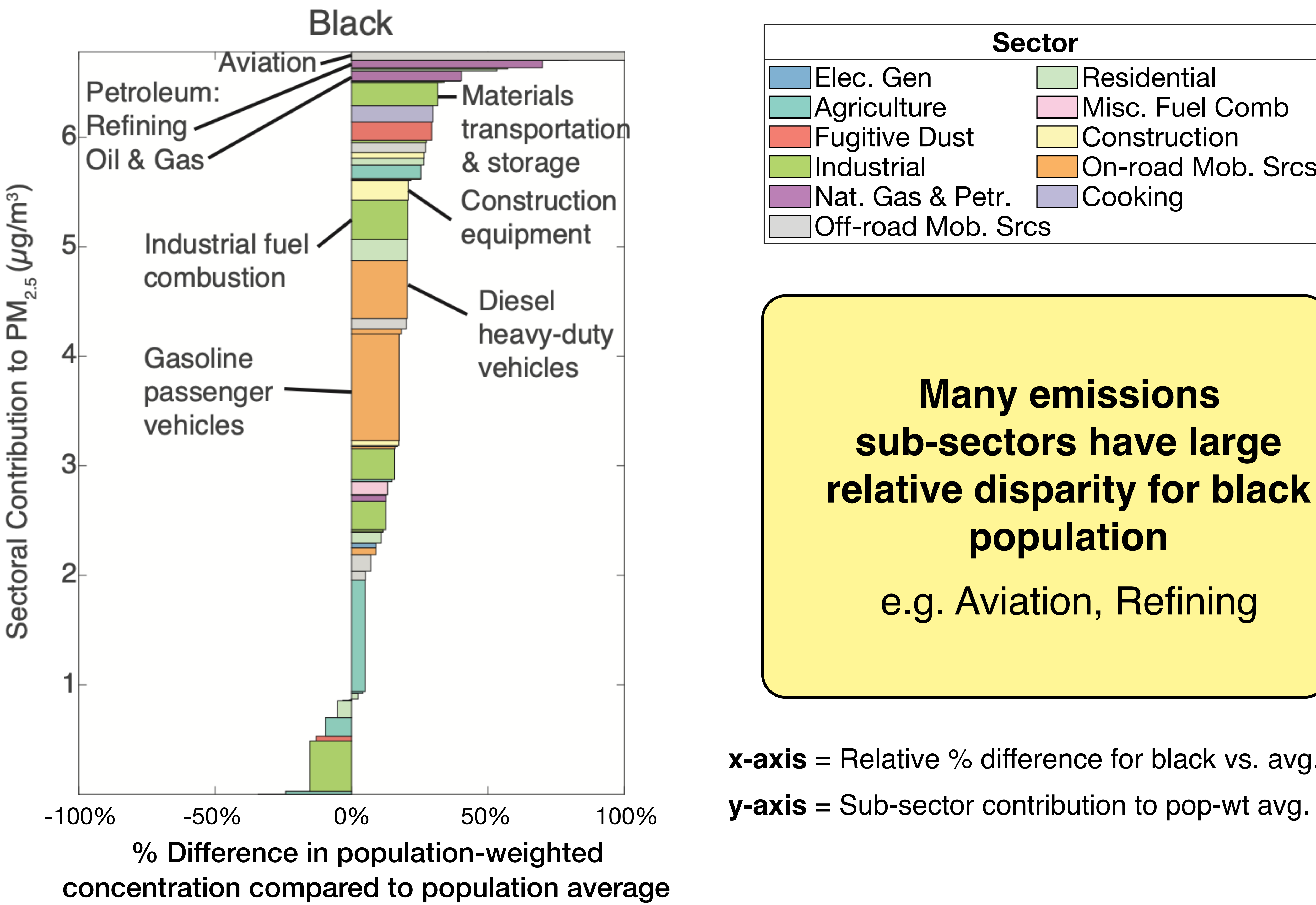
Net sector disparity in DACs: 0.3 µg m^{-3} $PM_{2.5}$.
Relative disparity: 52%

Largest contributions to disparity:

- Aircraft: 0.08 µg m^{-3} **(+100%)**
- Rail: 0.08 µg m^{-3} **(+100%)**

	Average	Total Δ for DACs (µg/m^3)	Relative Δ for DACs
Aircraft	0.08	0.08	100%
Diesel	0.10	0.05	55%
Gasoline	0.15	0.04	29%
Marine	0.09	0.01	7%
Other	0.01	0.01	63%
Rail	0.08	0.08	100%
Total	0.50	0.26	52%

Exposure disparity by sub-sector emissions



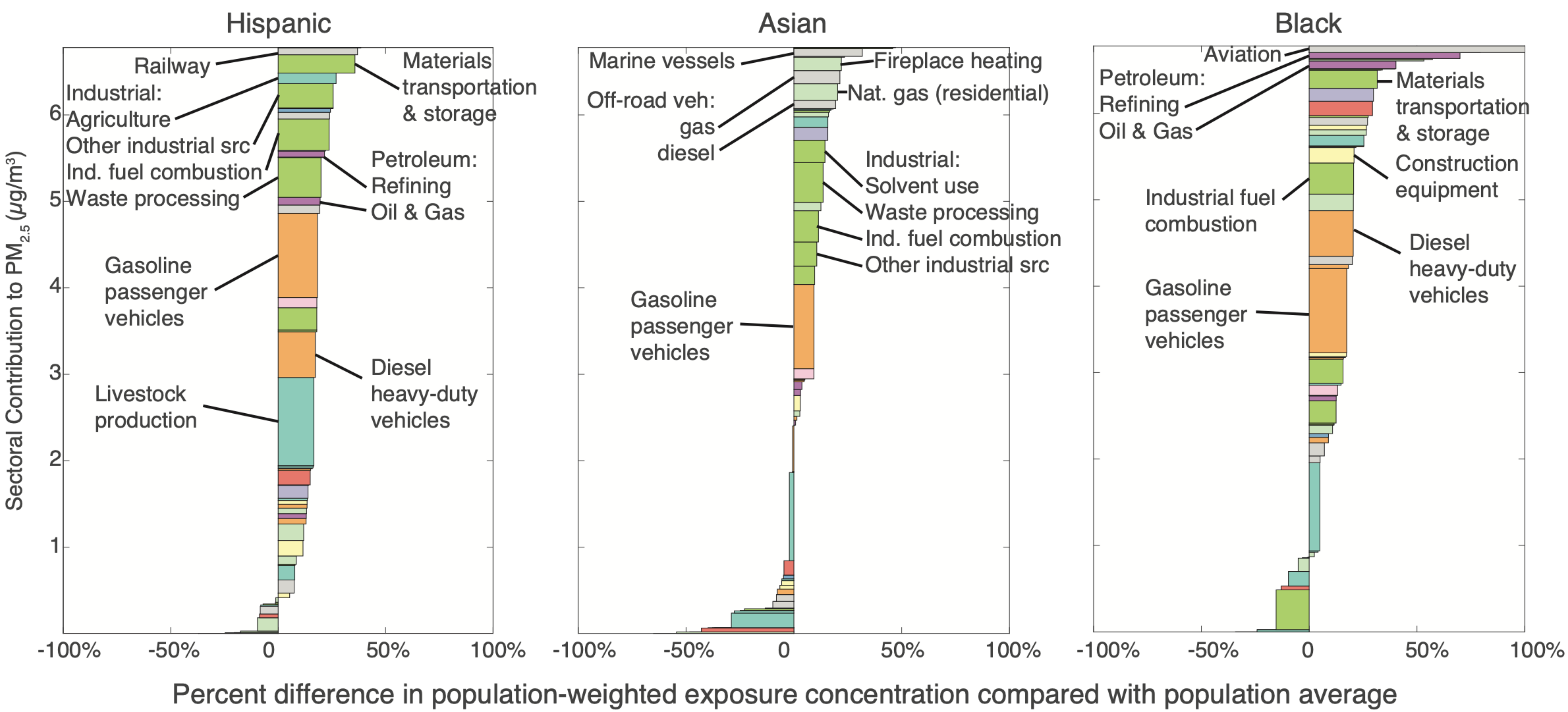
Many emissions sub-sectors have large relative disparity for black population

e.g. Aviation, Refining

x-axis = Relative % difference for black vs. avg.

y-axis = Sub-sector contribution to pop-wt avg. $PM_{2.5}$

Exposure disparity by sub-sector emissions



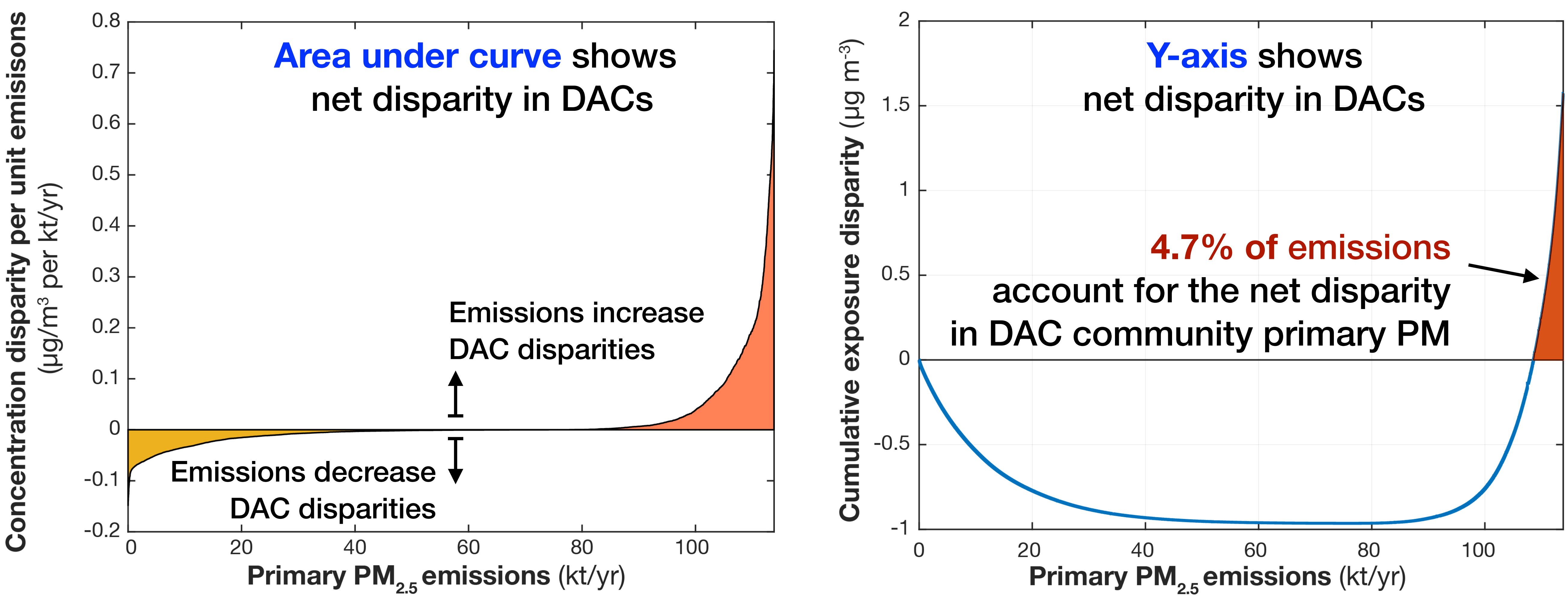
Sector	
Elec. Gen	Residential
Agriculture	Misc. Fuel Comb
Fugitive Dust	Construction
Industrial	On-road Mob. Srcs
Nat. Gas & Petr.	Cooking
Off-road Mob. Srcs	

Location matters.

Some emissions sub-sectors result in especially disparate exposures for certain races & ethnicities.

Exposure disparity in DACs: primary PM

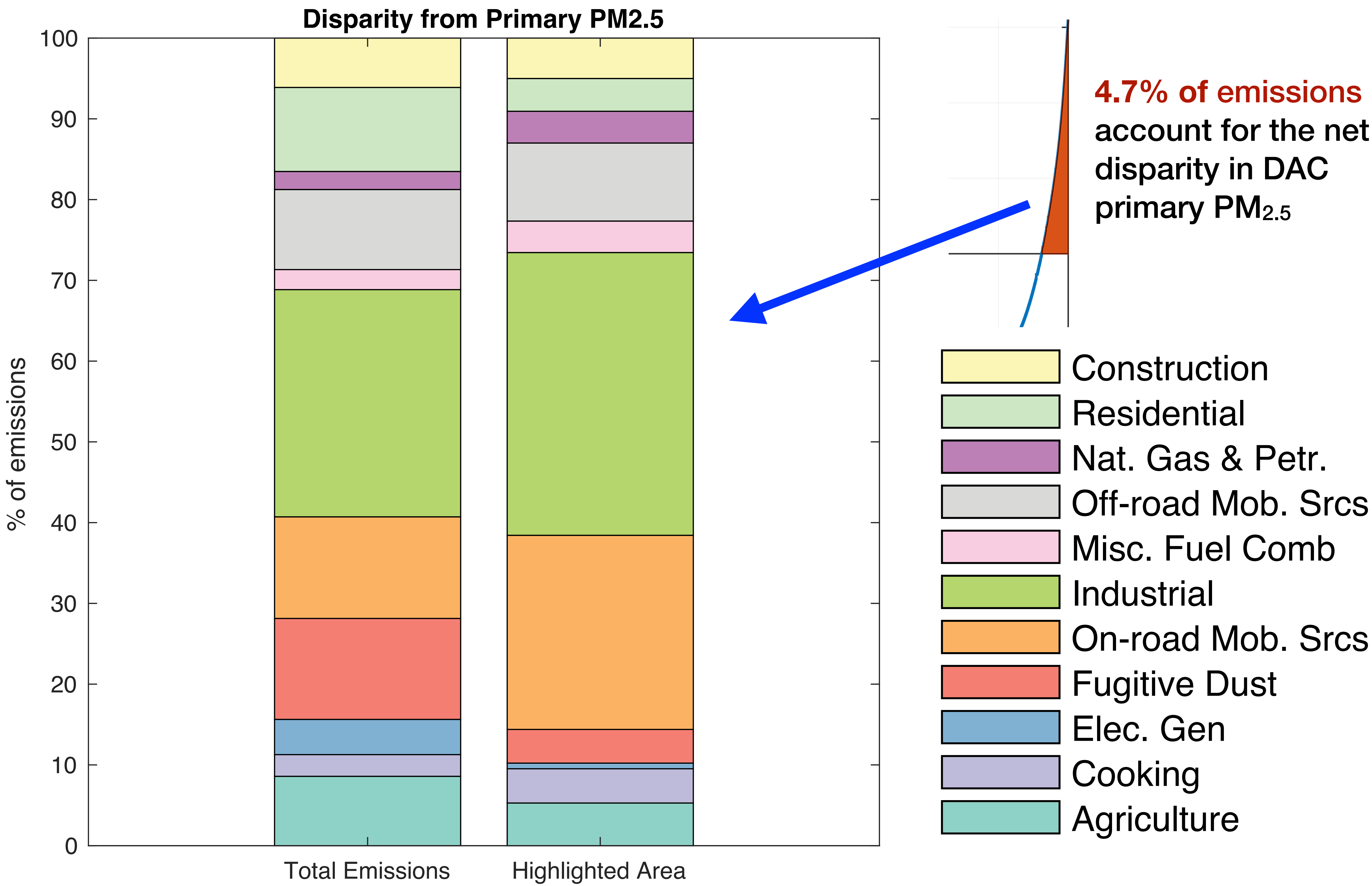
Disparity: concentration in disadvantaged (DAC) vs. non-DAC communities



Location matters.

< 5% of emissions drive the 1.6 μg m^{-3} primary $PM_{2.5}$ exposure disparity for disadvantaged vs. non-disadvantaged communities.

What sources drive DAC disparity?



Future research directions

- **Model development**
  - Apply this dataset to most up-to-date ARB emissions datasets.
  - Update InMAP chemistry for present-day and future atmospheres.
  - Compare and validate core sectoral results against other datasets: state-of-science atmospheric models, measurements, etc.

- **Analysis**
  - Evaluate metrics for specific regions and air basins.
  - Characterize exposure and EJ effects of possible decarbonization strategies.
  - Identify possible high-impact strategies to jointly reduce disparity & total exposure.

Key conclusions

- **Screening method** for linking CA emissions to intake and disparity.
- **Substantial disparities** by race. Smaller disparities by income.
  - 45% greater-than-average exposure in DACs.
- **No single "culprit":** nearly all sectors contribute to disparities.
  - High absolute disparity for DACs: on-road mobile, industry.
  - High relative disparity for DACs: oil and gas, off-road mobile
- **Location, location, location.** Dense urban environments have much higher iF than other release locations.
  - Emissions in high-iF locations have disproportionate impact on intake and on disparity/EJ.
  - Emissions location often explains differential impact more than the specific source category.

Tool and data will be publicly available. We invite you to use it!